Radiation studies on RFX

M.Valisa, L.Carraro, E.Casarotto, S.Costa, R.Guatieri, L.Marrelli, P.Martin, E. Martines,
A.Murari, Pasqualotto, M.E.Puiatti, F. Sattin, G. Serianni, P.Scarin, A.Schiavi

Gruppo di Padova per Ricerche sulla Fusione
ENEA-EURATOM-CNR-Univ. di Padova Association
Corso Stati Uniti,4 - 35020 Padova (Italy)

Introduction - In a Reversed Field Pinch (RFP) device impurities may degrade the plasma performance through direct energy losses and also affecting the relaxation phenomena by the change of the plasma resistivity profile, especially at the edge where the highly radiative ionization stages locate, ultimately causing an enhancement in the loop voltage. This paper summarizes the analysis of the radiation measurements performed on RFX [1]in 0.5 MA discharges in terms of impurity content, total radiated power and effective charge.

Experimental techniques - Impurity concentration measurements rely on absolutely calibrated spectrometers [2] which are used to monitor the hydrogen and helium like states of carbon and oxygen. The calibration of these instruments has been performed against a standard tungsten ribbon lamp in the visible and a deuterium lamp in the VUV and it has been transferred by means of the branching ratio technique in the XUV region. One of the spectrometers observes the plasma along nine vertical chords in order to study the radial emission profile of various ionization states while the others have standard equatorial views. The total power lost by radiation is measured by bolometer arrays at two toroidal locations. A triple Si(Li) detector and two neutral particle detector systems yield electron and ion temperatures respectively. Other electron temperature data are obtained from temperature sensitive line intensity ratios of C V and O V and from the Langmuir probe data in such a way that an electron temperature profile may be reconstructed. Impurity and hydrogen influxes are monitored by means of interference filters and a devoted spectrometer coupled via fiber optics to telescope lenses.

Impurity concentrations and radiated power -The analysis of the emission spectrum shows that the impurities present in the RFX hydrogen plasma are mainly carbon and oxygen. Nitrogen is generally below significant levels once the first wall has been adequately conditioned (less than 0.1%), while the emission spectra from 20 to 7000 Å are free of metal lines as a consequence of the extensive coverage with graphite tiles of the inconel vacuum vessel. Also the soft x-ray spectra collected with the PHA technique have never shown metal k_α peaks. With reference to 0.5 MA discharges, carbon concentration ranges typically from 1 to 3 per cent of the electron density for I/N values between 2 and 5 10^{-14} Am respectively. Oxygen concentrations have shown larger fluctuations during the experimental campaign according to the various wall surface cleanliness conditions. Here we will mainly refer to a situation characterized by 1 to 2 per cent of oxygen in the same I/N range as above. The error associated with these concentration values, taking into account calibration and computing procedures may not be considered better than 30%.

Within the experimental precision, the carbon relative concentration has not been found to vary significantly among discharges characterized by different field programming. During the flat-top phase carbon reaches approximately the same levels regardless of the way the maximum current has been reached, either by fast or slow ramp up, starting from high or low toroidal magnetic fields. Even the presence of a large number of arcs sometimes occurring during the current setting up or field reversal phase does not seem to compromise significantly the carbon content in the remainder of the discharge.

Little correlation has been found between carbon concentration and the amplitude of the field perturbations associated to modes locking [3] which cause strong local plasma wall interactions, with impurity influxes higher than elsewhere but in a relatively small fraction (~1/40) of the entire wall surface ($36m^2$), as observed by the CCD cameras equipped with C I and CII interference filters. There is also little correlation between carbon relative concentration and plasma shift for outward displacements up to 2 cm. In fact the poloidally distributed filter monitors show an increasing asymmetry in the impurity influxes with the plasma radial shift whereas the total influxes remain fairly constant. This is qualitatively shown in Fig. 1a where the ratio between the oxygen influxes measured at the innermost and outermost sides of a poloidal section is plotted as a function of the horizontal plasma displacement to be associated with the average influxes of Fig. 1b. The spread of the data, which refer to I/N values comprised between 2.5 and 3.5 10^{-14} Am, is mainly to be ascribed to the strong localization of the plasma wall interactions. The reason for this behaviour is that in RFX the plasma touches everywhere the large graphite surface in such a way that enhanced interactions on one side may be compensated by a reduced influx on another one. It is worth mentioning that from CCD observations only seldom the graphite surface temperature reaches 1000°C during the current flat-top so that enhanced sublimation processes may be excluded.

Fig.2 shows the behaviour of C V + C VI and O VII relative concentrations with I/N. An increasing trend is observed for O VII concentrations, while those of C V + CVI show a weaker dependence; actually, since the electron temperature increases with I/N (Fig.3), also the contribution of the fully stripped ions increases with I/N and so the total concentration. This is illustrated in Fig. 2 where the total carbon and oxygen concentrations computed for two I/N values by an impurity diffusion model are also indicated. The experimental data of Fig.2 are characterized by a degree of scattering which depends on the assumption of a fixed radial distribution in the plasma of the involved ion species and on the electron temperature used in the atomic coefficient calculations. Carbon and oxygen influxes decrease with I/N (Fig.4) but with a rate which is consistent with the behaviour of the correspondent impurity content in the main plasma.

As far as the impurity production mechanisms are concerned carbon influxes have not been found to be strictly correlated with the oxygen ones. In some circumstances following a filling gas contamination with water, an increase of a factor four of the oxygen influx did not affect the carbon one suggesting that carbon self sputtering or hydrogen induced sputtering are important for producing carbon more than the oxygen related processes.

The fractional radiated power decreases with I/N (Fig.5) and shows a radiation barrier below 2 10^{-14} A m while in general remains around 10-15 % of the ohmic input power.

Effective charge evaluation - On RFX Z_{eff} is evaluated from the ion abundances computed by means of a time dependent collisional-radiative 1-D transport code which simulates the absolute intensities and the profiles of the emission lines measured from a number of ionization states. The experimental impurity influxes and electron density and temperature profiles are used as input data. The standard technique to evaluate Zeff from visible bremsstrahlung radiation measurements, performed by means of interference filters centred at 5235 Å, has been found to be unreliable in our experimental situation, probably due to the presence of molecular bands, recombination radiation and/or unresolved lines in this spectral range. To study the emission lines by means of the 1-D code, a flat density profile determined from the interferometer [4] has been used. As to the temperature profile, the data deduced by tilting the Si(Li) detector of ± 15° on a shot to shot basis have been added to the intensity line ratios and Langmuir probe data, averaging over several similar discharges. In Fig. 6 the experimental data are compared to two analytical curves. The horizontal error bars on the line intensity ratio data refer to the width at half maximum of the related ion emission profile measured or self consistently estimated by the code. Within the experimental uncertainties, both the curves may approximate the data. In any case, as to the results of the diffusion code, the choice between these two curves is not relevant.

In fig.6 the ion temperature profile, derived from the neutral particle analyzers measurements by means of a Monte Carlo simulation, is also drawn , showing values quite similar to the electron temperature ones. The experimental situations corresponding to two values of I/N (2 and 4.5 10^{-14} Am) have been analyzed by the diffusion model assuming the same temperature profile. The results in terms of Zeff profiles are shown in Fig.7. Moving from low to high I/N values the central effective charge increases from about 2 to 2.5.

In order to verify the presence of an anomalous contribution to the plasma resistivity the estimated Z_{eff} could be compared with that deduced by an helicity balance model $Z^k=\eta^k(0)/\eta(0)_{Spitzer}$ Z=1 [5,6]. However the results of the comparison are so dependent on the temperature and Zeff profiles used to calculate Z^k to require an experimental precision which goes beyond the one associated to the present data. As an example,supposing a cubic-like profile for Te and a flat profile for Zeff, Z^k results 30% higher than the spectroscopic Z_{eff} implying an anomalous contribution of about 30% to the resistivity and therefore to the loop voltage.

Conclusions - Carbon and oxygen line emission absolute intensities and profiles have been measured in RFX, leading to relative concentrations of 1-3% for carbon and 1-2% for oxygen. Impurity influxes and electron temperature profiles have also been measured, allowing the simulation of the impurity behaviour by means of an impurity diffusion model for two different I/N values: the resulting on-axis effective charge ranges from about 2 for the low I/N example to 2.5 at high I/N. These relatively low Zeff values are consistent with the measured level of the radiated power, that in this I/N range has been found to be about 10 to 15% of the total input power. No pronounced correlations have been found between the impurity carbon content during the current flat-top with the plasma column outward shift as well as with the magnitude of the field perturbations caused by the locking of the modes.

References

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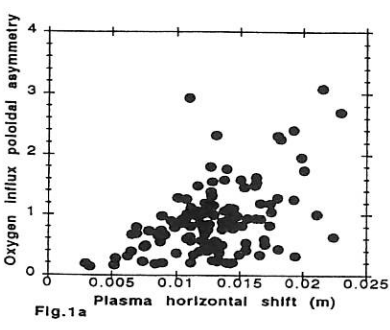

Fig.1a

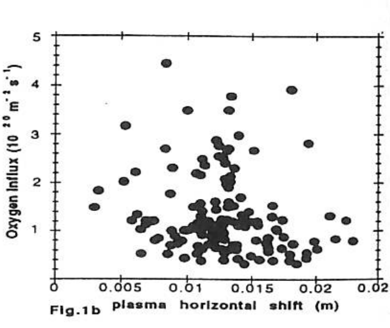

Fig.1b

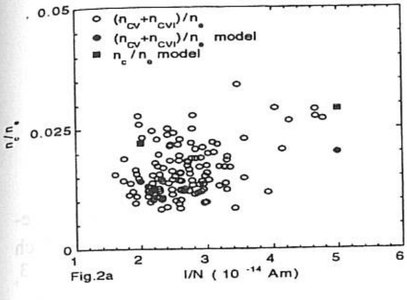

Fig.2a

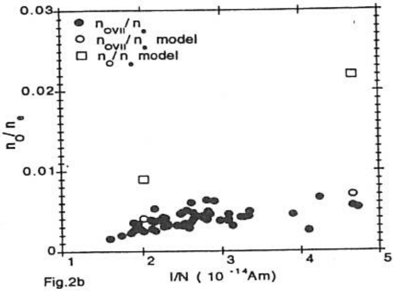

Fig.2b

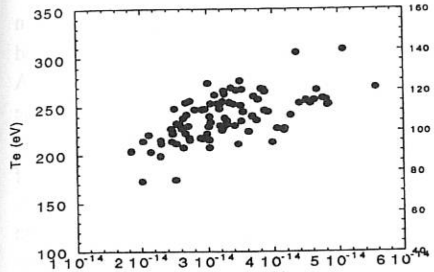

Fig.3

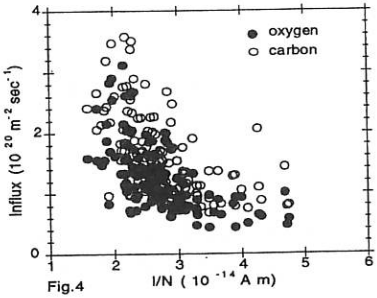

Fig.4

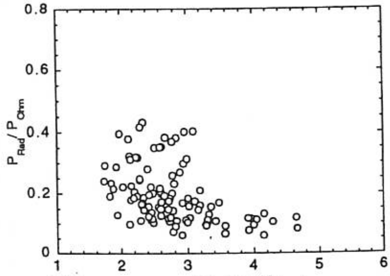

Fig.5

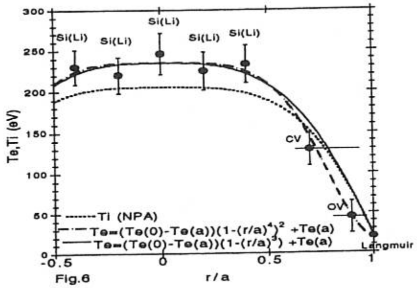

Fig.6

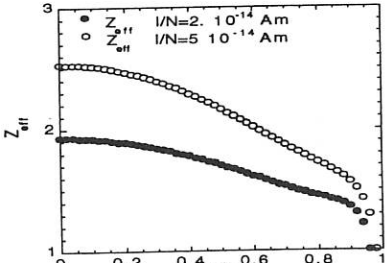

Fig.7