Impurity Transport of High Performance Discharges in JET

L Lauro-Taroni, B Alper, R Giannella, K Lawson[1],
F Marcus, M Mattioli[2], P Smeulders, M von Hellermann.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.
[1] Culham Laboratory, Abingdon, Oxfordshire, OX14 3DB, UK.
[2] Association Euratom-CEA sur la Fusion, Cadarache, France.

Long sawtooth-free periods are typical of high performance discharges in the JET tokamak (e.g Hot-Ion (HI) and Pellet Enhanced Performance (PEP) H-mode discharges).[1,2,3]

Depending upon the time duration of these quiescent phases, the degree of peaking of density and temperature profiles and the level of collisionality, as well as the shape of the q-profile, the light impurities' behaviour assumes different characteristics: either they accumulate towards the plasma centre, leading to various levels of depletion of the main plasma ions or, on the contrary, hollow profiles are measured, without any significant dilution effects on the fuel reactants. In general, medium and high-Z impurities play only a minor role.

The total radiation loss in the centre (up to ~50 kW/m^3) is in all cases much smaller than the local heating power. Also, the large excursion observed sometimes in the effective ion charge on axis (e.g. from $Z_{eff} \sim 1$ to $Z_{eff} > 4$ in some PEP discharges) does not lead to an important decrease of electric conductivity, because of a compensating effect due to the concomitant electron temperature rise. So the impurity behaviour appears not to be the cause of the abrupt MHD events [4,5] that normally terminate PEP or HI discharges, with the possible exception of cases close to marginal stability.

1.PELLET ENHANCED PERFORMANCE (PEP) H-MODE DISCHARGES

a. Analysis of Experimental Data

The clearest evidence of strong central impurity accumulation is supplied by the time evolution of the broad band soft X-ray and neutron emissivity profiles: when the neutron emission profiles decline and broaden, the SXR radiation from the central region increases.[2]

The VUV spectroscopic data indicate that the plasma main contaminants are C and Be and that Ni and Cl are also present. The absolutely calibrated line-of-sight measurements of the NiXXVII resonance line from the crystal spectroscopy indicates that the amount of Ni during the high performance phase is small: $n_{Ni} < 3\ 10^{-5}\ n_e$.

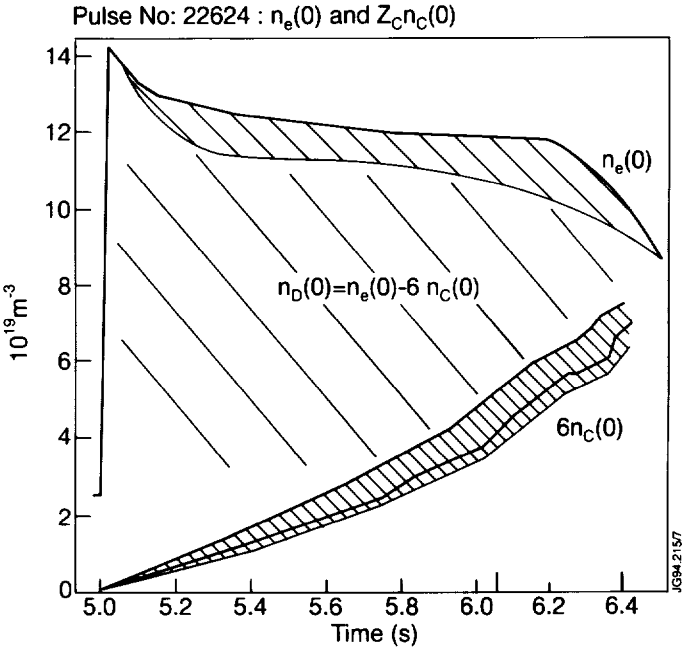

Fig.1: 22624. Time evolution of the central electron density and of the central density of electrons carried by carbon ions as estimated from $\varepsilon_{SXR}(0)$. Their difference is an estimate of the central deuterium density.

Both the VUV and the crystal spectroscopic data indicate that the Cl

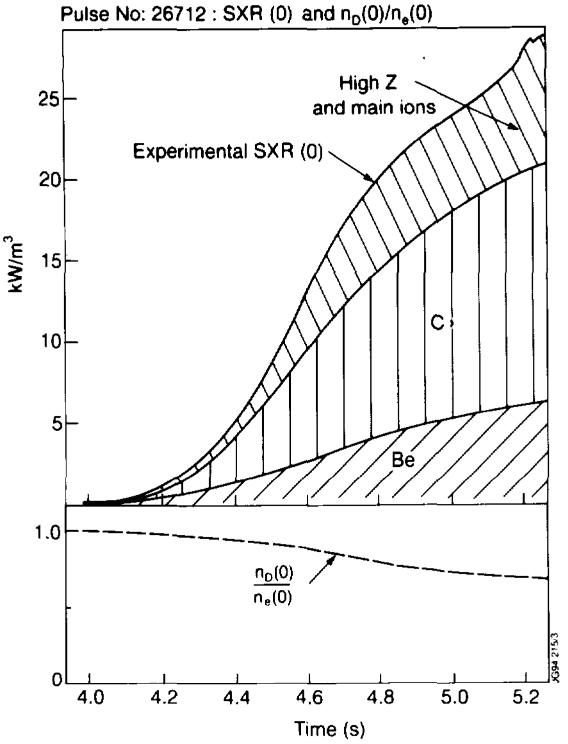

Fig 2. Above: time evolution of the experimental $\varepsilon_{SXR}(0)$ with its simulated components from Be and C for 26712. Below: simulated central fuel dilution.

content (usually varying in anticorrelation with Ni) does not seem to be significant in the high performance phase. So, the soft X-ray radiation from the central region is mostly due to light impurities (C and Be).

The soft X-ray emissivity from the plasma centre (where transport can be neglected) is

$$\varepsilon_{SXR}(0) = n_e \sum_{Z} n_Z(0) Q_Z(T_e(0), filter) \quad (1)$$

where $n_e(0)$ and $n_Z(0)$ are the electron and impurity central densities and the radiation coefficient Q_Z depends solely the impurity element, the central electron temperature $T_e(0)$ and the SXR Be filter [6].

To evaluate an upper limit for the central deuterium density $n_D(0)$, one can assume that a considerable fraction (70-80 %) of the central emissivity is emitted by C alone. Thus eq.(1) yields a reasonable estimate of the central carbon density $n_C(0)$. The central deuterium density $n_D(0)$ is then readily given by the quasi-neutrality condition, as shown in fig.1. It follows that the depletion of the main plasma ions in the central zone of the discharge can be severe for some PEP pulses, with $n_D(0)$ falling as low as $\leq 0.3\ n_e(0)$.

b. Impurity Transport Simulations

For PEP's, the impurity transport is anomalous in the outer region ($\rho \geq 0.5$, ρ being the normalised minor radius), and is dominated by convection (1-2 m/s) with a reduced diffusivity (D~0.1 m2/s) in the plasma core ($\rho \leq 0.4$)

Ni simulations, reproducing the absolute values and time evolution of the intensities of the available line brightnesses, confirm that its contribution (even if it varies from case to case) to the total $\varepsilon_{SXR}(0)$ is ~ 10 % or less. So, allowing for the bremsstrahlung radiation emitted by the main plasma ions, we conclude that 70-80 % of $\varepsilon_{SXR}(0)$ is due to low-Z impurities. Its simulation, assuming that C and Be are present in approximately equal amounts, requires high concentrations n_Z/n_e ~3 - 7 % in the centre, implying a depletion of deuterium in the same region.

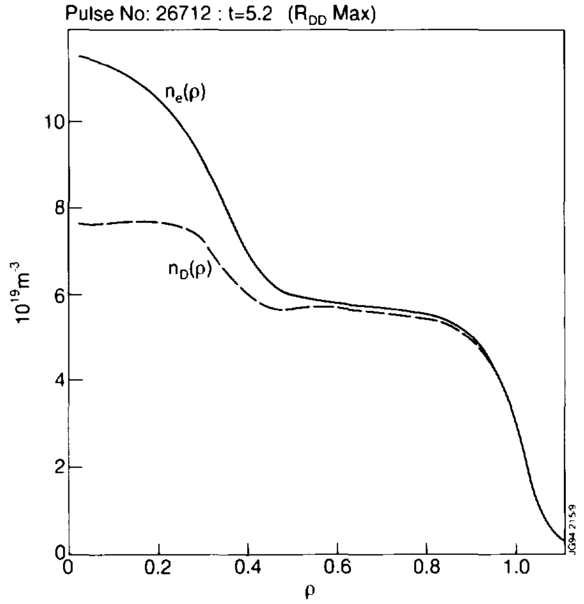

Fig.3: electron and deuterium (simulated) density profiles at t=5.2 s (max RDD).

For the pulse 26712 the depletion is mild (figs 2 and 3). In this case, neutron emissivity profiles were available. The simulated n_D profile at the time of the maximum neutron rate (fig.3) accounts for ≈ 55 % of the experimental neutron emissivity profile.

As the beam-thermal contribution is estimated to amount to ≈ 35 %, the n_D profile is consistent with neutron data.

In the case of the discharge 22624, the simulation confirms the analysis shown in fig.1. For that shot, unfortunately neutron data were not available, but carbon profiles from Charge Exchange Recombination Spectroscopy (CX) were, and they were well reproduced by the simulation.

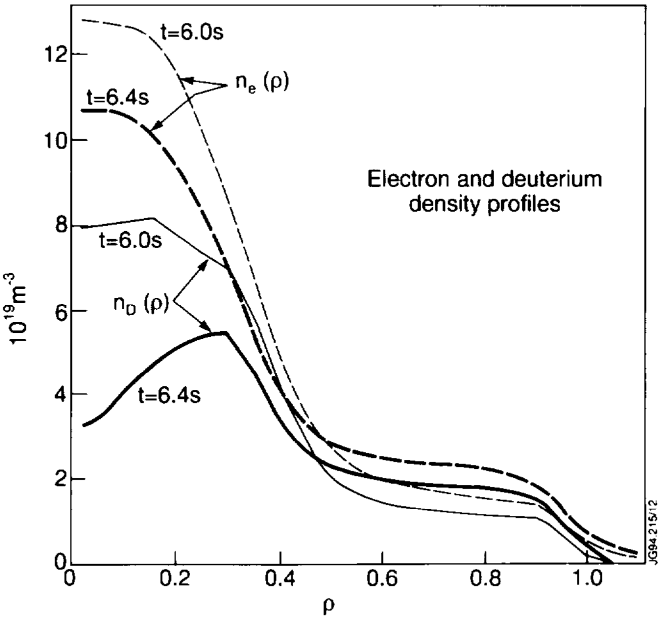

Fig.4.22624: $n_e(\rho)$ and $n_D(\rho)$ (simulated) at the times of max RDD (t=6.0s) and max fuel dilution (t=6.4 s)

Fig.4 shows the electron and deuterium (simulated) density profiles for pulse 22624 at the time of maximum neutron production (t=6.0 s) and their evolution at the later time t=6.4 s, when the central SXR emission reaches its maximum.

2.HOT-ION (HI) DISCHARGES

HI discharges have a low impurity content in the high performance phase. Heavy impurities are present only as traces ($n_{Ni}/n_e \sim 10^{-6}$-10^{-5}) and among low-Z impurities, C is dominant. These pulses do not show C central accumulation, but the profiles observed by CX are rather hollow (fig.5). C concentration in the plasma core ($\rho \leq 0.4$) is about $n_C/n_e \sim 1\%$, with no major effects on the fuel dilution.

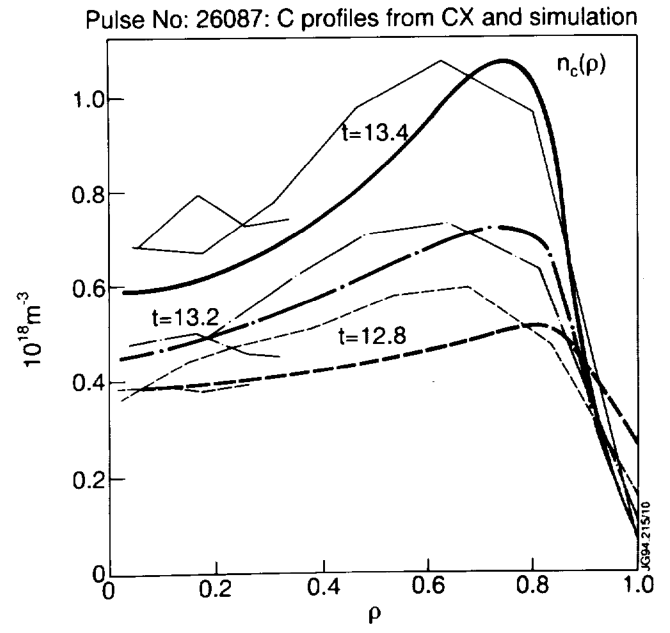

Fig.5: 26087 (HI). C profiles measured by CX at three times, plotted together with their corresponding simulated profiles (thicker lines)

The SXR emissivity from the centre is an order of magnitude lower than in the PEP's (few kW/m^3 for HI's against few tens of kW/m^3 for PEP's): it can be accounted for mainly by bremsstrahlung radiation from the main plasma ions.

The C transport in the central region is characterised for this case again by a reduced diffusion (D~0.1 m2/s), but the convective term is smaller (0.1 m/s) and directed outwards.

3. COMPARISON OF CARBON TRANSPORT IN THE PLASMA CORE: PEP vs HI.

Due to the different plasma parameters in the two cases, during the PEP shots C is well in the plateau collisionality regime, while it is in the banana regime during the HI pulses. In both cases the neoclassical diffusivity is low, of the same order as the heuristic values, but the dependence of the convection on the driving forces is different in the two cases (fig.6).

In PEP's C is usually in the plateau regime and the neoclassical convection specialised for these conditions is: $v_C^{nc} \propto \left(\frac{\nabla n_D}{n_D} + 1.13\frac{\nabla T}{T}\right)$, where T is the ion temperature.

In this case, the strong inward-directed term $\propto (\nabla T/T)$ can allow the accumulation towards the centre to continue even if ∇n_D changes sign.

In HI pulses C is usually in the banana regime and: $v_C^{nc} \propto \left(\frac{\nabla n_D}{n_D} - 0.3\frac{\nabla T}{T}\right)$

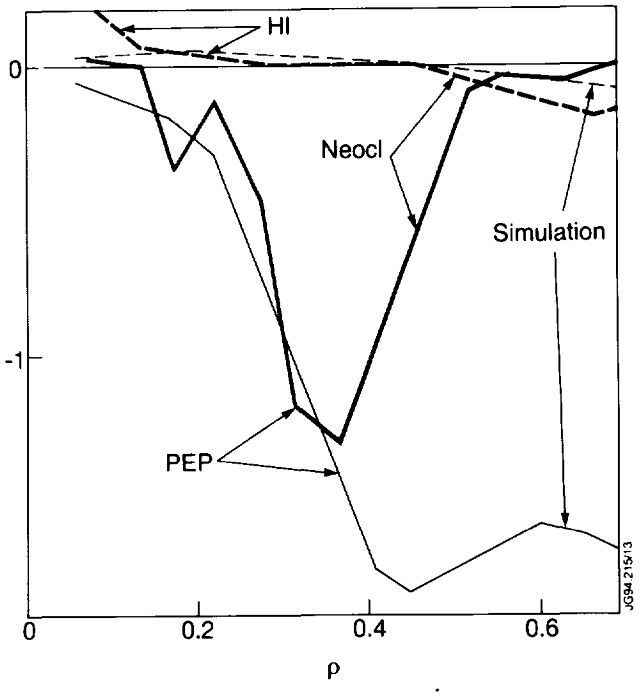

Fig.6: Comparison of the heuristic C convections used in the simulations for PEP (solid line) and HI (dashed line) and their corresponding neoclassical evaluations (thick solid line for PEP and thick dashed line for HI)

In this case, we can see a slight screening effect of the $(\nabla T/T)$ term: the accumulation is inhibited for peaked T-profiles when ∇n_D is small (which is the case for hot ion pulses in the plasma core)

CONCLUSIONS

The experimental data show that in the PEP-H discharges the light impurities are dominant and accumulate. Furthermore, strong fuel depletion may occur in the plasma centre with n_D/n_e falling to ~0.3 in some cases.

On the other hand, in Hot-Ion discharges hollow profiles are measured for C: it is present in lower concentrations and has little effect on fuel dilution.

The different behaviour of carbon in the two cases is in agreement with neoclassical predictions for the convection in the plasma core.

---

[1] D.Stork and the JET Team, Proc 4th IAEA TCM on H-mode Physics, 1994

[2] P.Smeulders et al, Survey of Pellet Enhanced Performance in JET Discharges, accepted in Nucl. Fus., 1994

[3] B.Balet et al, Energy Transport during the Pellet Enhanced Performance (PEP) Discharges in JET, Proc. Varenna Workshop on 'Local Transport Studies in Fusion Plasmas', Sept.1993

[4] G.Schmidt et al, (1987) Proc 11th International conf. on Plasma Physics and Contr. Nucl.Fus. Research, Kyoto Vol1, p.33

[5] R.Reichle et al, Termination of High Performance Discharges at JET, to be submitted to Nucl.Fus.

[6] H.P.Summers, Atomic Data and Analysis Structure, User Manual, JET Report, to be published, 1994