Local Measurement of Transport Parameters for Laser Injected Trace Impurities

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1. INTRODUCTION

The local measurement of transport parameters of a particle population essentially amounts to the analysis of the relationship between the fluxes Γ of that population and the spatial gradients ∇n of its density. In the study of transient radial propagation in a tokamak, this analysis depends exclusively on the possibility to measure, with adequate space resolution, n as a function of time.

Earlier attempts, however, to make use of time resolved tomographic soft X-ray diagnostics to infer directly the diffusivity D and convection speed V of injected trace impurities [1] were frustrated by the inconsistency between reproduced and measured data, when the profiles of D and V so inferred were used in the simulations of the injection experiments [2]. The obtained values of D, in particular, appear too high by a factor of 2 to 3 [3]. So far, therefore, the best method of transport analysis for these experiments has been the check of consistency of simulations of the impurity transport with the relevant diagnostic data.

Our analysis shows that the main source of error in Ref. [1] lies with the assumption that the density n_I of the injected impurity I can be deduced from the perturbation $\Delta\varepsilon$ induced by those impurities on the soft X-ray emissivity by the simple expression $n_I = \Delta\varepsilon/(Q_I \cdot n_e)$. Here n_e is the electron density and the radiation coefficient Q_I is assumed to be a function of the electron temperature T_e alone. Values of $Q_I = Q_{ICE}$ appropriate for the coronal equilibrium (CE) [4] were used in that work. It appears, however, that Q_I is not equal to Q_{ICE}. It is also not only a function of T_e, but of the time as well, depending on the state of motion of the injected impurity, that is in turn dependent on the transport parameters determining its propagation.

2. ITERATIVE PROCEDURE FOR DETERMINATION OF IMPURITY TRANSPORT

Based on the above observation an iterative procedure has been developed.

0 Using an initial guess (D^0 and V^0) for the profiles of D and V, a simulation of the entire phenomenon is performed producing a first tentative simulation of the impurity density $n^1_{ISim}(r,t)$, as well as of the perturbation to the soft X-ray emissivity $\Delta\varepsilon^1_{Sim}(r,t)$.

1 From that simulation a first estimate of the radiation coefficient Q^1_I is worked out as

$$Q^1_I(T_e(r),t) = \Delta\varepsilon^1_{Sim}(r,t)/(n^1_{ISim}(r,t)\cdot n_e(r,t)).$$

2 Using $Q^1_I(T_e,t)$, the first approximation n^1_I to the measure of n_I, is produced as

$$n^1_I = \Delta\varepsilon/(Q^1_I\ n_e).$$

3 Following Ref. [1] the first approximation to the flux $\Gamma_I^1(r)$ across the flux surface $S(r)$ is worked out as

$$\Gamma_I^1(r,t) = -\frac{1}{S(r)}\int_0^r \frac{\partial n_I^1}{\partial t} dV$$

and consequently the first approximations to $D(r)$ and $V(r)$, $D^1(r)$ and $V^1(r)$ are deduced by fitting, at every radial position r, a straight line to the plot of $\Gamma_I^1(r,t)/n_I^1(r,t)$ versus $\nabla n_I^1(r,t)/n_I^1(r,t)$:

$$\frac{\Gamma_I^1(r,t)}{n_I^1(r,t)} = -D^1(r)\frac{\nabla n_I^1(r,t)}{n_I^1(r,t)} + V^1(r). \qquad (1)$$

4 A new simulation is then run, using profiles for the transport parameters $\hat{D}^1(r)$ and $\hat{V}^1(r)$ that are derived (as explained below) from D^1 and V^1, that leads to the second simulations of the impurity density, $n_{ISim}^2(r,t)$, and of the perturbation to the soft X-ray emissivity, $\Delta\varepsilon_{Sim}^2$, as in the preparatory step 0 above.

- Repeating then steps 1 to 4 new approximations are found for Q_I, n_I, D and V.

In a few iterations (say N) the procedure is seen to converge (see fig. 1) supplying the measured profiles of the transport parameters D^N and V^N (only extending up to a certain radial position as explained below) as well as the best estimate of the extended profiles $\hat{D}^N$ and $\hat{V}^N$.

This procedure intrinsically assures consistency of the obtained transport parameters with the experimental emissivities. In fact, if the ansatz expressed by equation (1) is compatible with the data, close agreement is also found between the limit determinations of n_I and their simulations n_{ISim}, as well as between the simulated emissivities $\Delta\varepsilon_{Sim}$ and the measured values $\Delta\varepsilon$ (see fig. 2).

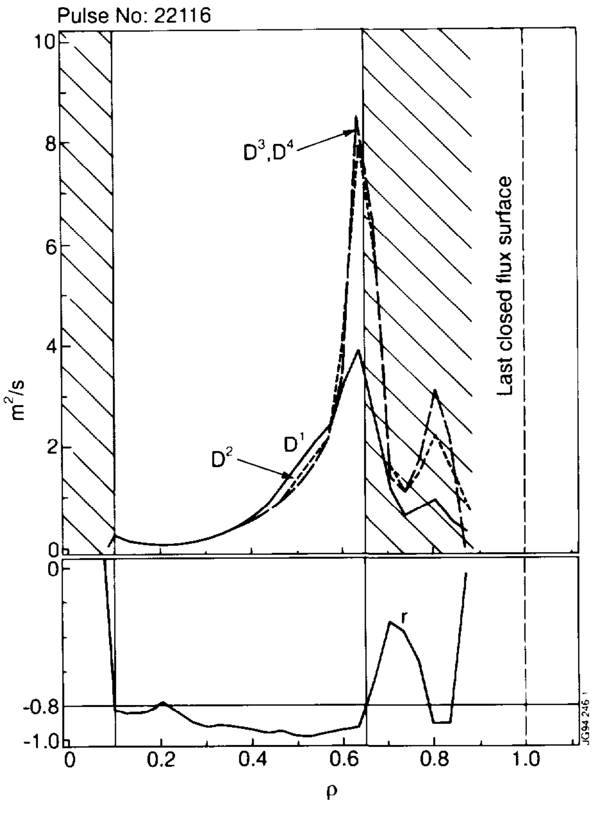

Fig. 1 **Successive determinations D^n of the impurity diffusion coefficient. The correlation coefficient r of the linear regression (step 3 in the iterative procedure) for the determination of D and V, as obtained at the last iteration, is also shown. The shaded area represents the radial region where, due to the emissivity $\Delta\varepsilon$ being too low, correlation is poor and the deduced values of D, are unreliable.**

3. CONSTRAINTS ON THE SIMULATIONS AND ERROR ANALYSIS

Due to the relatively thick (250 μm) Be filters used in the JET soft X-ray tomographic diagnostic, the detected emissivity profiles are very weak outside a certain radius leading to increasing uncertainties outside that position. Because of this, the measure of transport parameters by means of the regression fit (fig. 3) is only reliable in a certain core region ($\rho < 0.6 - 0.8$).

The estimate of $Q_I(T_e,t)$ however depends on the whole time history of the impurities from their ingress in main plasma. The simulation therefore needs D and V profiles up to the plasma edge. In order to complete the radial description of impurity transport, the soft X-ray

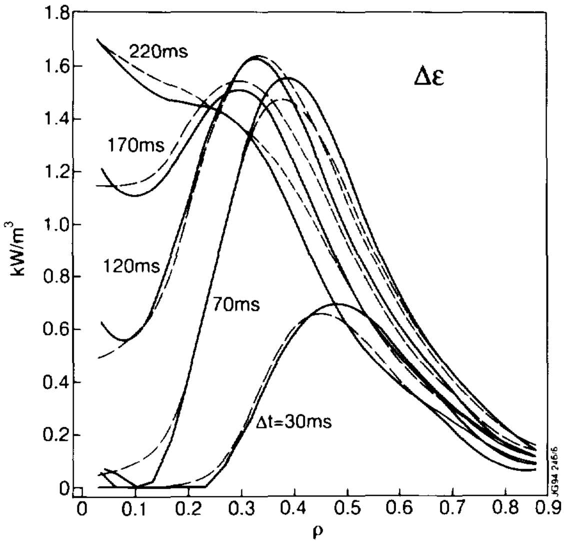

Fig. 2 **Experimental (solid lines) soft X-ray line emissivities at different times Δt following injection of Ni into the plasma. The broken lines represent the simulation of the emissivity as obtained at the end of the iterative analysis procedure.**

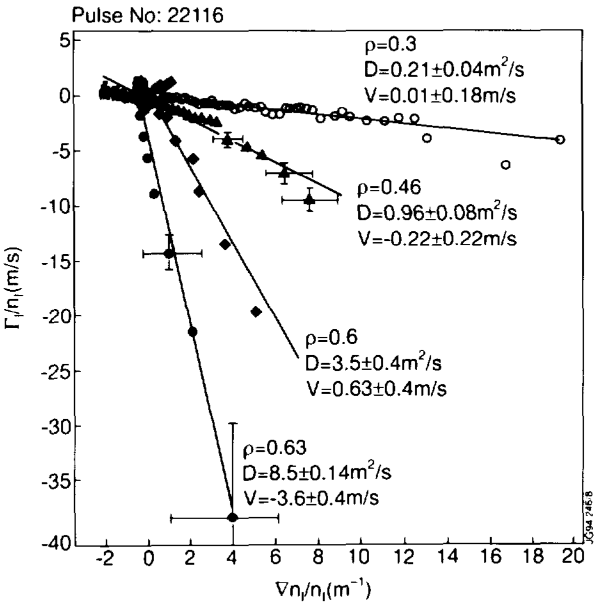

Fig. 3 **Normalised fluxes Γ_I/n_I and density gradients $\nabla n_I/n_I$ at four radial positions as obtained at the last iteration in the iterative analysis procedure. The best fitting straight lines, the deduced local values of the transport parameters and their uncertainties are also indicated.**

data need to be supplemented by the brightnesses of lines from individual ion states emitted in the VUV domain.

To this end step no 4 in the above mentioned iterative procedure really consists of a search for a most suitable extension in the outer region to the transport parameters, obtained by optimizing the simulation of a number of VUV and soft X-ray line brightnesses.

This is the most CPU-time consuming step in the whole procedure. In fact the optimization is performed by minimizing the time integral of the squared differences between the experimental and simulated brightness signals. The minimizing routine calls typically 100 times the simulation program equivalent to about 40 minutes of CPU with the IBM

3090/300-J mainframe computer at JET. The whole iterative procedure requires, until convergence, ~ 120 minutes of CPU-time

The error analysis, performed on a statistical basis, attributes to the different time slices and space points different weights according to the calculated uncertainties on Γ_I and ∇n_I. It shows that the most useful phase typically extends from 20 - 40 ms to 100 - 200 ms after the injection, depending on the particular space point. In fact during the first few tens of milliseconds the perturbative signals are too low and the limited space resolution of the diagnostics introduces large systematic errors on ∇n_I. After the first few tenths of a second, on the other side, the reliability of the signal is impaired by the growing uncertainty on the background radiation.

4. TREATMENT OF SAWTOOTH CRASHES

For pulses where sawtooth activity is present, the simulation has to reproduce the rearrangement in the impurity density profile that occurs at the sawtooth crashes. This rearrangement is simulated by interrupting the one-dimensional diffusive-convective transport at a time t_1, 1 or 2 ms before the crash, and restarting it at a time t_2, 3 or 4 ms later, with a new initial condition for the density n_{zSim} of each ionization state z of the injected impurity:

$$n_{zSim}(r,t_2) = R\,\frac{n_{zSim}(r,t_1)}{n_{ISim}(r,t_1)}\,n_I^*(r,t_2)$$

where $n_I^*(r,t_2) = \Delta\varepsilon(r,t_2)/(\hat{Q}_I(r,t_2)\cdot n_e(r,t_2))$, $R = \int n_{ISim}(r,t_1)\,dV \,/ \int n_I^*(r,t_1)\,dV$,

$$\hat{Q}_I(r,t_2) = \frac{\sum_z n_{zSim}(r,t_1)\,q_z(T_e(r,t_2))}{n_{ISim}(r,t_1)}$$

and $q_z(T_e)$ is the radiation coefficient for the z ion state.

5. CONCLUSIONS

A procedure has been developed that determines local measurements of transport parameters' profiles for injected impurities. The measured profiles extend from the plasma centre up to a certain radial position (usually $\rho = 0.6 - 0.7$).

In the outer region of the plasma the procedure supplies *"most suitable extensions"* up to the plasma edge of the measured transport profiles.

The procedure intrinsically assures consistency and excellent agreement between the simulated and experimental data of local broad band soft X-ray emissivity and intensities of individual emission lines from different ion states of the injected impurities.

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