Particle transport determined from modulated gas puff

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The paper discusses the particle transport which is determined through modulated gas puff experiments in ASDEX Upgrade. The Thomson scattering data is used for the analysis, and a so called forward method is used to determine the transport coefficients.

Because the modulated ECRH experiments do not show any density modulations the equation that describes the density evolution is assumed independent of the temperature. The density (n) evolution is assumed to be given by the linear equation

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rD(r)\frac{\partial n}{\partial r} + rV(r)n\right] + S(r,t) \qquad r(\psi) = \frac{1}{\pi}\sqrt{\frac{\mathcal{V}(\psi)}{2R_m}}, \tag{1}$$

where $S = S(r,t)$ is the particle source, and $D(r)$ ($V(r)$) is the diffusion (convection) coefficient. The transport operator is written in cylindrical coordinates with r being the effective radius of the flux surface labeled by the poloidal flux ψ, R_m is the major radius of the magnetic axis, and $\mathcal{V}$ is the volume enclosed by the surfaces on which the poloidal flux is ψ.

Method of analysis

A so called forward method is used to determine the transport coefficients. In this method the transport equation is solved for certain values of the transport coefficients. Using a non-linear fitting algorithm the transport coefficients are adapted until the solution of the transport equation (1) fits best to the measurements. If radial profiles of the coefficients are to be found, this procedure is an under-determined problem. Therefore, one has to limit the number of possible solutions. It is preferable to find the smoothest profile of the coefficients that is allowed by the measurements. Such a solution can be found by regularization.

The code that performs the analysis solves the transport equations in the region where $S(r,t) \approx 0$, for a given set of frequencies, mostly the modulation frequency only. The diffusion (D) and pinch (V) coefficient are given on a grid of the radial coordinate, r_i $i = 1 \to N$. The transport equation is then solved and the solution n_c is determined at the radial points (r_j $j = 1 \to M$) where the density is measured by Thomson scattering. The nonlinear fit procedure then minimizes the following function

$$F(D(r_i), V(r_i)) = \mathcal{R} + \frac{1}{2}\chi^2, \tag{2}$$

where

$$\mathcal{R} = \alpha \frac{\sum_{i=1}^{N} (\partial D_i/\partial r)^2}{\sum_{i=1}^{N} D_i^2} + \alpha \frac{\sum_{i=1}^{N} (\partial V_i/\partial r)^2}{\sum_{i=1}^{N} V_i^2} \tag{3}$$

and

$$\chi^2 = \sum_{j=1}^{M} \left(\frac{\Re n_c(r_j) - \Re n(r_j)}{\sigma_j} \right)^2 + \left(\frac{\Im n_c(r_j) - \Im n(r_j)}{\sigma_j} \right)^2. \tag{4}$$

Here, n is the measured density profile, σ is the standard deviation of the measurement, and $\Re$ ($\Im$) denotes the real (imaginary) part of the Fourier amplitude. Minimizing the last term in equation (2) yields the normal least square fit to the data. Minimizing the first term yields a solution for which the gradients of the coefficients are minimized, i.e. a smooth function. The coefficient α is chosen such that the obtained fit lies within the error bars of the measurements. In this way a fit to the data is found which is both acceptable and has the most smooth radial profiles of the diffusion and pinch coefficients.

Results

As an example two shots will be discussed, one (#8005) in which the working gas is Deuterium and one (#8618) in which the working gas is Hydrogen. The gas puff is modulated with a frequency of 5 Hz. The plasma parameters of the two shots are similar, and are given in table 1.

Table 1. Plasma parameters of the analyzed shots

shot	gas	I_p	B_t	n 10^{19} m^{-3}	T_e keV
8005	D_2	1 MA	-2.5 T	4.6	1.4
8618	H_2	1 MA	-2.5 T	5.1	1.1

The diffusion coefficient and pinch velocity for the Deuterium case obtained from the 5 Hz component is shown in Fig. 1 together with the obtained fits to the data. The results for the Hydrogen case are shown in Fig. 2. The error bars on the diffusion and pinch are estimated using different sets of data points. These error bars only show how the uncertainty in the measurement influences the determination of the transport coefficients within this method. Of course non-smooth profiles of the coefficients can be constructed for which the solution fits just as well to the data. In this sense the error bars are arbitrarily large.

The diffusion coefficient increases towards the plasma edge. A large inward pinch is found at the edge. The transport coefficients for the case with Hydrogen are higher compared with the Deuterium case. These results agree with those previously found on ASDEX [1].

The question whether the obtained transport coefficients from the modulation also explain the steady state profiles is investigated by simultaneously fitting the Fourier amplitude of the modulation frequency and the steady state profile. The agreement for the Deuterium case is reasonable (it must be noted that V in this case is not accurately determined from the 5Hz component, see Fig. 1), whereas no good fit is obtained in the Hydrogen case.

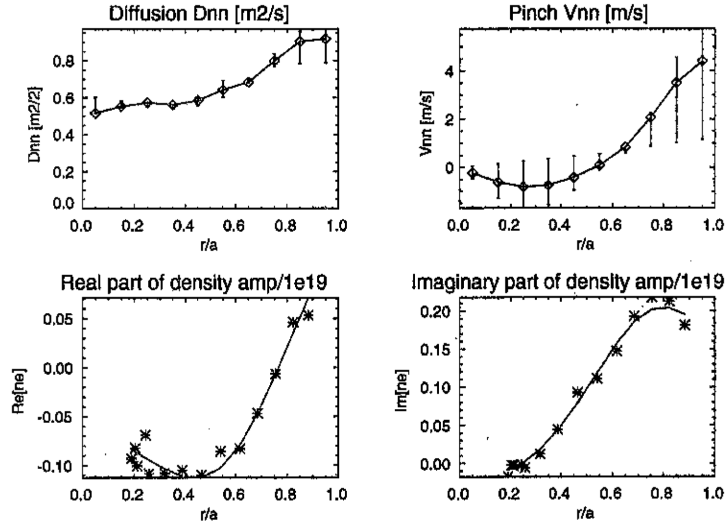

Fig. 1. Obtained results for the Deuterium case

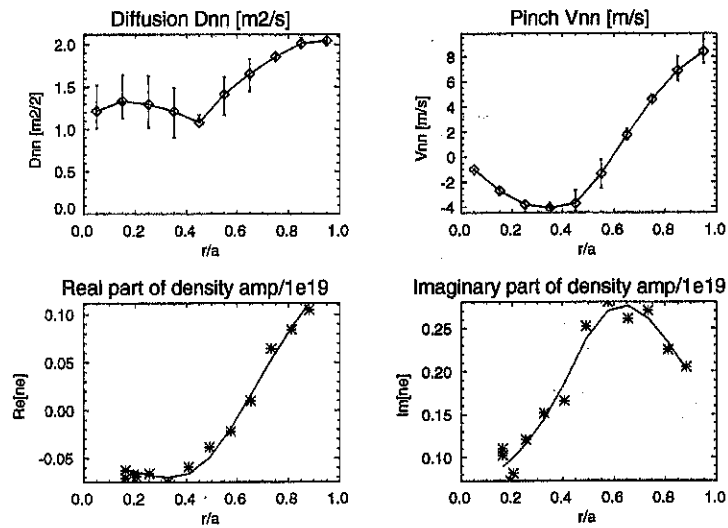

Fig. 2. Obtained results for the Hydrogen case

Temperature perturbation during modulated gas puff

During the modulated gas puff experiments a large temperature perturbation is observed, which increases in amplitude towards the plasma centre. This in contrast to the density perturbation which decreases in amplitude. This temperature perturbation nevertheless can be explained largely from the convective terms in the linearized energy balance

$$\frac{3}{2}n\frac{\partial\tilde{T}}{\partial t} = \nabla n D_{\mathrm{TT}}\nabla\tilde{T} - \frac{5}{2}\tilde{\Gamma}\nabla T_0 - T_0\nabla\tilde{\Gamma} - \frac{3}{2}T_0\tilde{S} + \tilde{Q}_{\mathrm{heat}}, \qquad (5)$$

where the tilde denotes the perturbation and the index zero the unperturbed quantity. In Eq. (5) T is the temperature, Γ the particle flux, and Q_{heat} is the external heating (in this case Ohmic heating). With the particle transport determined the measured temperature can be fitted with Eq. (5), in which one new unknown appears, the heat diffusion coefficient D_{TT}. A reasonable fit can be obtained as shown in Fig. 3. The heat diffusion coefficient, however, is larger that the ones obtained in modulated ECRH experiments, which indicates that other terms in the transport equation might play a role. In future experiments modulated gas puff and modulated ECRH experiments will be combined to determine the coupling more accurately.

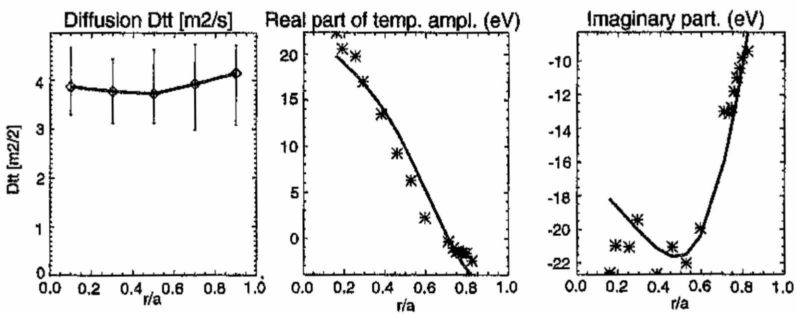

Fig. 3. Results of the fit to the temperature perturbation (Deuterium case).

Conclusion

The transport coefficients can be determined accurately from Thomson scattering using the forward method. This method has the advantage that no processing of the data is necessary, which would lead to additional sources of errors. The most smooth profile of the coefficients obtained by the method allows for a study of the radial dependence.

References

[1] K.W. Gentle, O. Gehre, K. Krieger, Nucl. Fusion **32**, 217 (1992).