MEASUREMENT OF TRANSIENT PARTICLE TRANSPORT COEFFICIENTS IN W7-AS

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1. Introduction

The understanding of the particle transport in fusion devices is as important as the understanding of the energy transport. The particle transport is less studied than the energy transport due to larger experimental difficulties. In particular, perturbative particle transport experiments have the problem that both the production of density perturbations and accurate measurements of small perturbations in the plasma density are difficult to obtain.

The earlier experimental knowledge of the transport in the bulk plasma in the W7-AS stellarator has been based on transport studies made with equilibrium methods (particle balance) [1-3]. According to these studies the diffusion coefficient depends inversely on density and increases with heating power. The density dependence leads to an increase of the diffusivity in the plasma edge region. The particle balance method however does not separate between diffusive and convective fluxes.

A 10-channel microwave interferometer [4] was build at W7-AS for advanced time dependent particle transport investigations, which allow for a separation of diffusive and convective contributions to the particle transport. This paper reports on extensive transient particle transport studies carried out with the multichannel interferometer. The density perturbations were produced by modulating the gas feed to the plasma, as described in [5].

2. The method

Electron density perturbations were produced by modulating the particle source. The signal driving the gas valve was modulated sinusoidally which produced a harmonic perturbation propagating from the plasma edge to the center. Because the main particle source in W7-AS comes from the limiter, the perturbation of the source was small providing a density perturbation of 1-5 percent of the local density.

The 10-channel microwave interferometer measured the line integrals of the electron density. The electron density perturbation, i.e. the Fourier-coefficients of the density at the modulation frequency, are determined from the line integrals by inverting the real and the imaginary part separately with the inversion method described in [6].

In order to model the propagation of the density perturbation we solved the radial, Fourier-transformed particle transport equation [5]:

$$i\omega\tilde{n}(r) = \left(\frac{1}{r}\frac{\partial}{\partial r}r\right)\left(-D\frac{\partial}{\partial r}\tilde{n}(r) + V\tilde{n}(r)\right) + \tilde{P}(r). \quad (1)$$

Here r is the radius, ω is the gas puff modulation frequency, and thus the frequency of the harmonic perturbation propagating in the plasma. $\tilde{n}$ is the electron density perturbation, i.e., the Fourier-transform of the density at the gas puff modulation frequency ω. D is the diffusion coefficient and V is the convective velocity (if the sign is negative it is an inward directed pinch). $\tilde{P}$ is the modulated perturbative electron source simulated with the Monte-Carlo code EIRENE [7].

The measured complex perturbation profile is fitted with the simulated perturbation profiles solved from Eq. (1) by varying the transport coefficients D and V. The diffusion coefficient was a constant independent of the radius and the convective term was modeled with the expression $V = (a/(1 + exp(-(r + b)/c)) + d)(r/r_{boundary})$. To summarize, D had one parameter and V four: a, b, c, d. Increasing the amount of the parameters of D overparametrized the fitting problem. A fit example is illustrated in Fig. 1 and the resulting transport coefficients are sketched in Fig. 2. Note, that the inward convection occurs at the radial region where the amplitude grows in the direction of the propagation. This cannot be explained without an inward convective term.

3. Results

We carried out scans in the electron density (line averaged density $\bar{n} = 0.5...3\times$ 10^{19} m^{-3}, which equals to 1...6$\times10^{19}$ m^{-3} peak density), ECH heating power $P_{ECH} = 180...470$ kW, and the magnetic field B = 1.25 T and B = 2.5 T. The rotational transform ι was always approximately 1/3 and the separatrix at 0.17 m. The regression analysis of the results from nearly 50 discharges gives a scaling for the transient particle diffusion coefficient of the form:

$$D = (0.84 \pm 0.05)n_e^{-1.18\pm0.13}T_e^{0.69\pm0.22}B^{-0.51\pm0.22}. \quad (2)$$

Here n_e is the central electron density in 10^{19} m^{-3}, T_e is the central electron temperature in keV and B is the toroidal magnetic field in T. The resulting dimension of D is m^2/s. The scaling is not valid in the region $r \geq 0.12$ m. The transport in the outer region is driven also by the convection and therefore the diffusion coefficient in that region is not well defined (we fitted constant D). Since only two interferometer channels go through the plasma center, the scaling might not be relevant at $r \leq 0.05$ m.

The earlier particle balance diffusion coefficient scalings in W7-AS are as follows. Ref. [1] reports power degradation of the diffusivity and that the doubling of the magnetic field makes D three times smaller. In [2] (an edge transport study) D scales like $1/(nB)$. The temperature dependence was only marginal. In [3] $D \sim 1/n^2$ or $D \sim 1/(nT_e)$ was not distinguishable. Our density dependence agrees with all these studies, but there are differences in the temperature and magnetic field scalings. These differences can be commented in two ways. The particle balance studies are mainly valid in the outer region where our scaling is not valid. Furthermore, particle balance studies give in fact scalings of the total particle flux and not diffusion coefficient. Therefore the existence of a pinch at the boundary most likely causes this difference. Secondly, equilibrium and perturbation scalings may differ, if D depends e.g. on ∇n. Altough we did not see difference in our density scalings (see below).

In the inner plasma, the convective flux is negligible compared with the diffusive flux (in the example case Fig. 2, $r \leq$0.12 m), only in the outer plasma $r \geq$0.12 m the convection plays important role.

We did not find any clear dependence for the convective coefficient in the edge on plasma parameters. The magnitude of V at the outer region was typically -10 to -100 m/s. However, there is a relation between the radial point up to which the pinch is active (b in the model of the convection coefficient) and the radial point R_v where the density gradient region ends. This is illustrated in Fig. 3. The values for R_v were calculated from density profiles measured with Thomson scattering, thus independently of the multi-channel interferometer. The correlation found is a clear evidence that the density gradient in W7-AS is driven not only by the particle source but also by the inward convection. The inward convection might be driven by e.g. the turbulence in the outer plasma region.

4. Outward convection

Outward convection was detected with an ECH power $\geq$ 600 kW in shots with a hollow density profile. The analysis was not possible without a significant outward convective term in the inner plasma. With ECH of 1.3 MW, the density perturbation peaked at the plasma edge and could not propagate into the plasma. The opposite could be expected since the particle balance studies [1] with ECH power degradation predict a large diffusion coefficient D and hence a fast propagation to the center. With a large D, the data can be explained only if V is outward directed. A natural explanation for the outward convection is the neoclassical ∇T-term. Therefore we speculate, that the inward pinch might exist also in the inner plasma but is cancelled by the ∇T-driven outward transport for the smaller ECH powers.

5. Comparison with the equilibrium transport coefficients

The equilibrium transport coefficients can be calculated from the simulated equilibrium source profiles (EIRENE) and the measured electron density profiles. A comparison between the perturbative and equilibrium particle diffusion coefficient is illustrated in Fig 4. The ECH power was 470 kW, the magnetic field 2.5 T, $\iota \approx$ 1/3, and $\bar{n}$=1,2 and 3 $\times 10^{19}$ m^{-3} (the middle density is shown). The coefficients agree within the error bars in the region not affected by the inward convection for all three densities.

References

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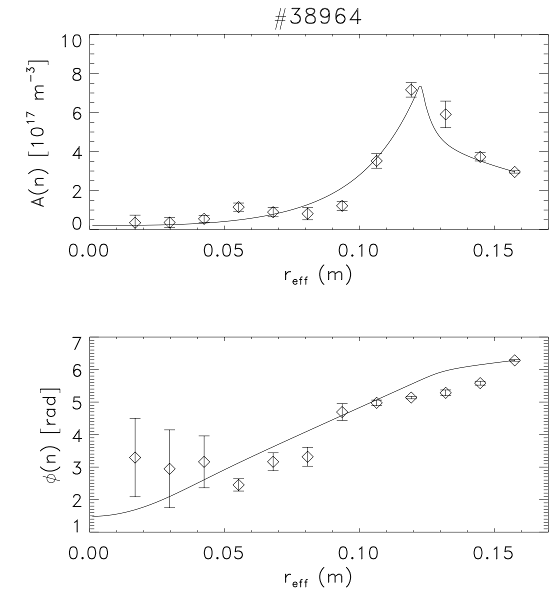

Fig. 1. Amplitudes and phases and fits of density perturbations in #38964.

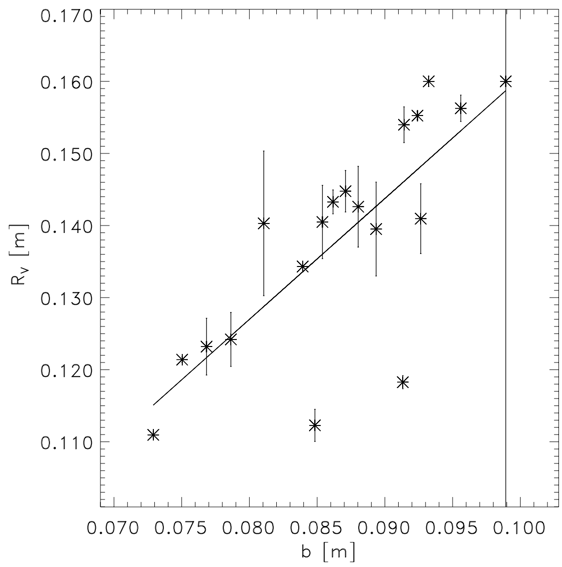

Fig. 3. Radius R_v where the density gradient ends vs. radius up to which V is active.

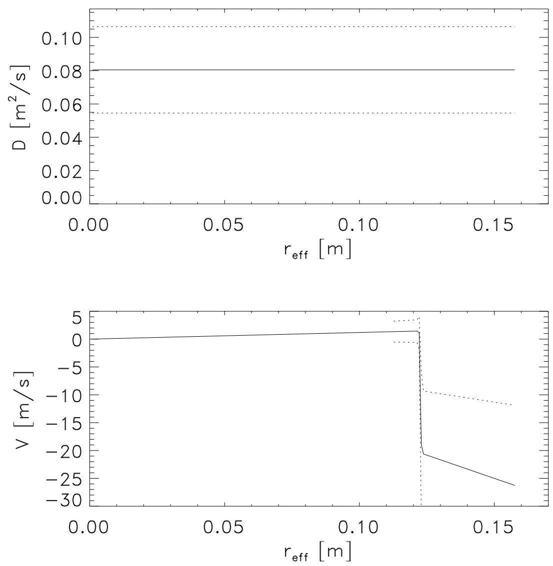

Fig. 2. Diffusion coefficient and convection coefficient V resulting from the fit in Fig. 1. Dashed lines are error bars.

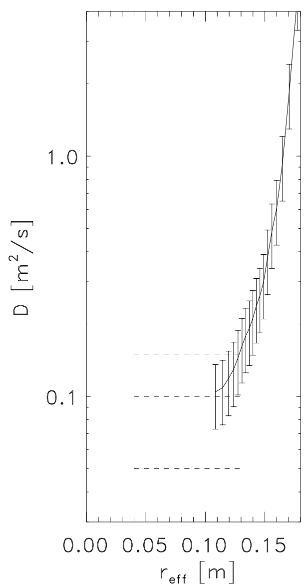

Fig. 4. Comparison between the equilibrium (solid line) and perturbative diffusion coefficients (dashed lines), discharge 38964.