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Evidence for Convective Inward Particle Transport in W7-AS

J.P.T. Koponen[1], T. Geist[2], H.-J. Hartfuß[2], H. Laqua[2], U. Stroth[2], Ch. Wendland[2], E. Würsching[2], and ECRH and W7-AS teams[2]

[1]*Department of Engineering Physics and Mathematics, Helsinki University of Technology, Euratom-TEKES Association, Espoo, Finland*
[2]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstrasse 2, D-85748, Germany*

Introduction: Radially peaked density profiles were observed in the W7-AS stellarator in a plasma heated only with ECH [1]. Monte-Carlo simulations with the EIRENE code excluded the possibility of relevant central particle sources. Particle balance analysis revealed the existence of convective inward particle flux. In addition, density modulation experiments were performed in discharges with peaked density profiles. The peaked density profiles appear only in discharges with flat temperature profiles as a consequence of extremely off-axis ECH. This suggests that in the discharges with peaked T_e profiles the inward convection is canceled out by the outward directed thermodiffusion. New experiments were carried out in the recent campaign. The dependence of the density peaking on ECH power and density was studied. As a new result we found that strong gas puffing prevents the formation of the peaked density profiles.

Phenomenology: Density peaking was observed when strong off-axis heating was used. The ECH microwave mirror position was scanned and the resulting density profiles are shown in Fig 1. With the mirror position S=0, the deposition is on-axis and the density profile is flat and corresponding temperature profile is peaked. With S=7 cm, the profile has not yet peaked. The corresponding temperature profile is not any more peaked in the plasma centre. The density peaking is strongest when S = 10.5 cm. If the deposition is made more off-axis, the plasma becomes relatively cold and also the density peaking disappears.

Anticorrelation between density and temperature profile peaking: In equilibrium the particle flux is zero and we can write the following formula for the density diffusion coefficient D_{11}, off-diagonal element D_{12} and the pinch u:

$$\left|\frac{\nabla n_e}{n_e}\right| = -\frac{D_{12}}{D_{11}}\left|\frac{\nabla T_e}{T_e}\right| - \frac{u}{D_{11}} \qquad (1)$$

The $\nabla n_e/n_e$ is plotted as the function of $\nabla T_e/T_e$ in the Fig. 2. The transport coefficients can be estimated in this way only very roughly since no radial dependence of the transport coefficients is allowed. Anyway, Fig 2 shows clearly, how density profiles are peaked when temperature profiles are flat and vice versa.

Transient Transport Analyses: To obtain precise values for the particle transport coefficients, two independent techniques were used. Firstly, the temporal evolution of the density was modeled with the transport code ASTRA. Secondly, gas modulation experiments were carried out. The transport coefficients were deduced from the propagation of density perturbations from the plasma edge to the center. Modeling of the density perturbation propagation requires introduction of inward pinch.

Both the time dependent and the modulation analysis yield a diffusion coefficient of $D_{11} \sim 0.2\ \mathrm{m^2/s}$ in the core. The agreement obtained in the time-dependent analysis by fitting the measured local densities with ASTRA simulations with suitable transport coefficients was good. The density rise and drop determined the particle diffusion coefficient D_{11} in the center. The transition from a flat to a peaked density profile can be well reproduced. The evolution in the plasma center is obtained with an almost constant transport coefficients and can be explained with ∇T_e-driven transport. The outward directed convection due to the ∇T_e-term is balanced by an inward pinch during on-axis heating. By switching the heating to off-axis, the temperature gradient disappears and the density peaks due to the inward pinch.

Dependencies on heating power and density: We studied the effect of ECH-power on the density peaking in the recent experiment campaign. We used heating powers 400, 600 and 800 kW. Fig 3. shows the density profiles from discharges with different powers of off-axis heating at the line-integrated density $\bar{n} = 2\mathrm{x}10^{19}\ \mathrm{m}^{-3}$. The density peaking is not strong with higher heating powers. Especially with 800 kW the profile is rather flat. The same experiment was performed also at higher densities, $\bar{n} = 4\mathrm{x}10^{19}$ and $6\mathrm{x}10^{19}\ \mathrm{m}^{-3}$. The results were similar to the results shown in Fig 3, altough the difference between density profiles at 400 and 800 kW was not so large in the highest density case as in the smallest density case.

The density peaking was strongest with the line-integrated density $\bar{n} = 4\mathrm{x}10^{19}\ \mathrm{m}^{-3}$, and almost equally strong as in the case of the smallest line-integrated density shown in Fig. 3. The peaking was relatively smaller in the shots with highest line-integrated density.

Sensitivity to the gas puff: The new experiment campaign revealed that the peaking effect is sensitive to the gas puffing level or corresponding edge density. We observed, that strong gas puff increasing the edge density does not allow formation of the peaked density profiles. This effect was revealed by an experiment with three different density plateaus. The line-integrated density $\bar{n}$, the average peaking parameter $\nabla n/n$ between 2 and 8 cm and the gas puff signal are shown in Fig 2 (from top to bottom correspondingly). As the density is increased (Fig 2 upper frame), gas is puffed strongly to the vacuum vessel (Fig 2 lower frame). The peaking parameter (Fig 2 middle frame) drops to zero during the strong gas puff, but rises rapidly after the strong gas feed has been ended. We were not able to achieve the peaked density profile operation during good wall conditioning and low recycling conditions needing rather strong gas puffing through the whole discharge. The peaked density profiles discussed in [1] were achieved in rather high recycling conditions with low gas puff level. The edge densities were smaller in the high recycling cases than in the low recycling cases. The temperature profiles were flat in both cases due to the off-axis heating.

This behaviour is somewhat similar to the reheat effect observed in CHS [2] where the central electron density increased 80 % after turning off the gas puffing. In our discharge #46282 shown in Fig. 4. the central density rose almost 20 % between time points 0.91 and 1.08 s. In CHS the diamagnetic energy W_p did not rise during the peaking. Generally in our experiments the diamagnetic energy is slightly reduced during the density peaking due to the drop in the central temperature. It was found in the impurity accumulation studies of CHS that the inward convection increased dramatically (by a factor 20) after the gas puffing had been ended. In CHS a correlation between the density peaking factor and the absolute value of the poloidal rotation was found. Also the role of large negative electric field was important in CHS. Unfortunately we lack data of these plasma parameters.

Summary: Peaked density profiles were found in discharges heated purely with ECH without significant particle sources in plasma centrum. This can be explained with inward particle convection. Inward convection is observed also in the edge region of W7-AS during on-axis heating with gas feed modulation experiments [3]. The density profile peaking was stronger with smaller off-axis ECH power. No difference between off-axis ECH deposition above and below the plasma centre was found indicating that the ∇B-drift is not responsible for the density peaking. Since the observed pinch is in variance with neoclassical transport theory it should be caused by plasma turbulence.

The density profile peaking is possible only when the electron temperature profile is flat, and the gas puffing is weak. The observed dependence of the pinch on the gas puff level suggests that there exists a strong coupling between the plasma edge parameters and the core turbulence level.

References:

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[2] S. Morita et al, in Plasma Physics and Controlled Nuclear Fusion Research 1992 (Proc. 14th Int. Conf. Würzburg, 1992), Vol. 2, IAEA, Vienna 1993, 515.
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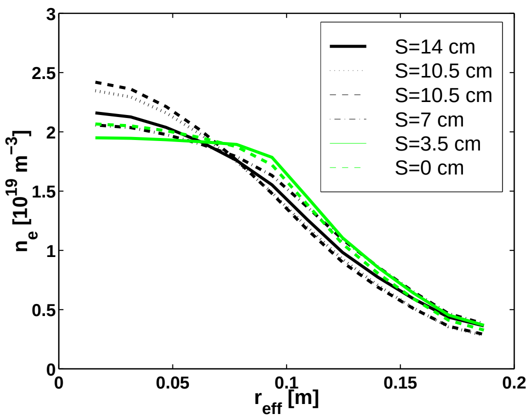

Fig 1: *Density profiles from discharges 45455–45457 and 45461–45463 with various ECH mirror positions S.*

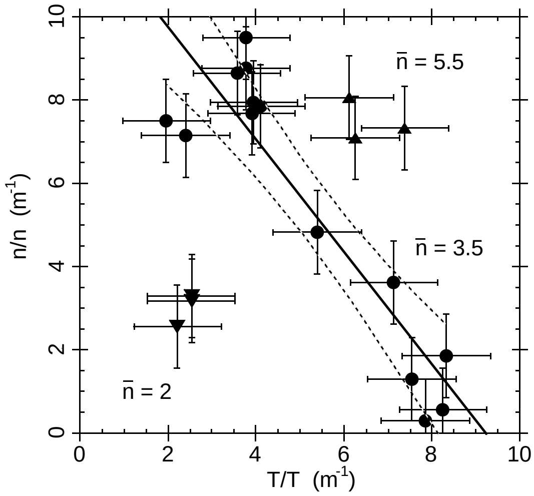

Fig 2: *The average density gradient scale length correlates with the average temperature gradient scale length. The fit yields values for the coefficients in the Eq. 1:* D_{12}/D_{11} *= 1.4 and* u/D_{11} *= -12.5* m^{-1}.

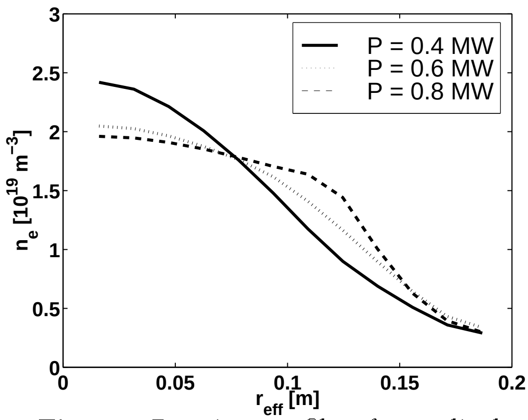

Fig 3: *Density profiles from discharges with different powers of off-axis heating. The density peaking decreases with increasing heating power. The profiles are from discharges 45457 (P=0.4 MW), 45507 (P=0.6 MW), 45508 (P=0.8 MW).*

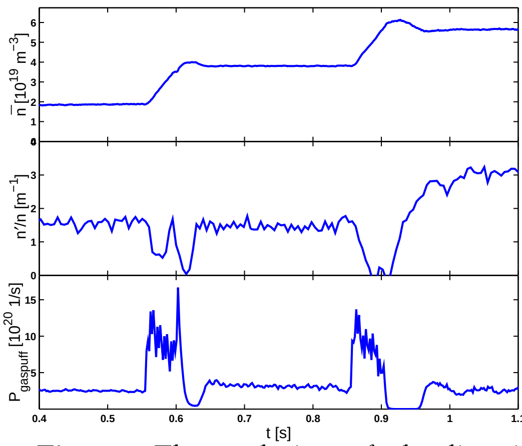

Fig 4: *The evolution of the line integrated density during the discharge 46282 is shown in the upper frame. The correponding average density peaking parameter is shown in the middle frame and the gas puff signal in the lower frame. The density profile flattens strongly during the strong gas puff period, and peaks rapidly after the strong gas puffing has been ended.*