Time–resolved Transport in W7–X as predicted by Neoclassical Theory

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In next–genaration stellarators such as W7–X, recycling and gas puffing affect only the edge of the plasma. Hence, an active density profile control via central particle sources, e.g., NBI and/or pellets, is needed. To reach a certain experimental plasma density, the central particle source is not only determined by diffusive losses due to the density gradient as for instance in tokamaks. The off–diagonal elements of the neoclassical transport matrix become essential in the stellarator long mean free path (LMFP) regime which is mandatory for the central region of W7–X plasmas. Especially the off–diagonal term which is related to the particle balance predicts additional particle losses due to the temperature gradient.[1] Hence, strong temperature gradients together with too small a central gas refuelling rate will drive the density hollow, i.e. a positive density gradient has to compensate the off–diagonal losses to fulfil the particle balance. On the other hand, too large a filling rate may give rise to increasing density and decreasing temperature.

Neoclassical Transport Matrix

The neoclassical particle and energy flux densities, Γ_α and Q_α, with $\alpha = e, i$, are given by

$$\Gamma_\alpha = -n_\alpha \{ D_{11}^\alpha (\frac{n_\alpha{}'}{n_\alpha} - \frac{q_\alpha E_r}{T_\alpha}) + D_{12}^\alpha \frac{T_\alpha{}'}{T_\alpha} \}$$

$$Q_\alpha = -n_\alpha T_\alpha \{ D_{21}^\alpha (\frac{n_\alpha{}'}{n_\alpha} - \frac{q_\alpha E_r}{T_\alpha}) + D_{22}^\alpha \frac{T_\alpha{}'}{T_\alpha} \}$$

with q_α being the particle charge and with the "convective term" $(3/2)T_\alpha \Gamma_\alpha$ included in Q_α. The radial electric field E_r is determined by the roots of $Z_i \Gamma_i = \Gamma_e$. The neoclassical transport coefficients D_{jk}^α (with j,k=1,2) are determined from the mono–energetic transport coefficients, e.g., $D_{1/\nu} \sim 1/\nu$, $D_{\sqrt{\nu}} \sim \sqrt{\nu}$ and $D_\nu \sim \nu$ with ν being the collision frequency [2,3].

In order to show the time evolution of the density and the temperature profile, the ASTRA code [4] is used in a stellarator specific version [5] with the full neoclassical transport matrix for the W7–X high–mirror configuration [6] (see Fig. 1). The ambipolar E_r is calculated by direct iteration yielding the so–called "ion root" which is expected for the plasmas of interest here. For simplicity, $n_e = n_i = n$ is used in all cases. To yield quantitative estimates about the central refuelling rate which is needed to reach a scenario with non–hollow density and pressure profiles calculations are performed at various heating powers of up to 20 MW (electron heating only) and for different initial conditions of densities and temperatures.

Need for Central Particle Refuelling

As can be seen from Fig. 2, too large a central heating and too small a central refuelling rate produces a hollow density profile as expected from theory [1]. In this case, the start conditions are $n = 1 \times 10^{20}$ m^{-3}, $T = 1$ keV, $P = 10$ MW. The filling rate is 1×10^{20}

s^{-1}. Here, a strong temperature gradient driven by the heating cannot be balanced or exceeded by the external particle source. While the density gradient becomes positive, the negative electron temperature gradient is increased by the increased value of heating power per particle, driving the density gradient more and more positive. Hence, no stationary situation is reached here and the whole central density may be lost within a few hundred milliseconds. In this case also an inverted pressure profile occurs with $p' > 0$, which may drive MHD instabilities.

Enlarging the central refuelling rate to over–compensate the particle losses which are caused by the strong off–diagonal term of the transport matrix coupled to the temperature gradient yields an almost contrary situation. The hollow density profile is observed only at the beginning of the discharge owing to the start conditions. At later times, when the influence of the start conditions is more and more lost, the high refuelling rate is able to drive a steep density profile. Close to the plasma edge, however, the high temperature together with an unfavourable scaling of the transport coefficients result in local particle fluxes which generally are less than the central refuelling rate. A transport barrier occurs. Due to this barrier, the central density increases and becomes more and more peaked. Both temperatures decrease slowly and become identical, as can be seen from Fig. 3 (refuelling: 15×10^{20} s^{-1}; n: 2×10^{20} m^{-3}; T: 1 keV; P: 10 MW). As far as an active control of the central particle source is possible, e.g. via pulsed pellet scenario, this behaviour is less critical than the case shown in Fig. 2. This situation does not differ much by changing the density and temperature start conditions, as can be seen from Fig. 4. This figure shows also that independent from the start situations three different regimes can be distinguished: The low rate regime, where the whole central density may be lost within less than a few hundred milliseconds; the high rate regime with highly peaked and increasing densities and lifetimes of a few seconds before the pressure profile becomes hollow due to almost vanishing central temperatures; and the intermediate regime with almost constant plasmas. The rate needed for this intermediate regime is almost proportional to the heating power, i.e. the filling rate must be close to 1×10^{20} m^{-3} per second per MW heating power according to the value determined in [1] with stationary calculations.

Further, simulations show that not only the total particle source is linked to the total heating power. To reach non–hollow pressure profiles, the radial profile of the particle deposition must be strongly correlated to the power deposition profile. In all cases with almost stable conditions, both profiles are nearly identical. With a too narrow or too broad particle source, either the density or the temperatures are driven hollow, depending on the total refuelling rate. The reason for this behaviour can be found from the strong coupling of the transport equations in the central region. Assuming sufficiently high temperatures, the radial electric field can be neglected. Solving the stationary equations for the filling rate yields an ambipolar particle flux which is roughly proportional to the energy fluxes of the electrons and the ions. Here the radial dependences of the transport coeffiecients cancel each other. Hence, the particle refuelling profile is similar to the power deposition profile.

In W7–X, this strong coupling is necessary for the high–mirror configuration. Lowering the toroidal mirror term will change the local behaviour of the transport coefficients with the effect of broader refuelling profiles which are less coupled to the heating profile. Central refuelling, however, will be mandatory.

Transport Barrier at outer Radii

At outer radii, the neoclassical particle flux must exceed at least the central particle source. Otherwise the outer density increases and the global density control is lost. In this region, however, the neoclassical transport coefficients of the electrons are much smaller than those of the ions. Solving the transport equations for the particle flux at outer radii shows that the ambipolar partical flux can simply be described as being proportional to D_{11}^e and the normalized temperature gradient. For the same reason, the ion energy flux is close to the whole energy flux, which should be equal to the central heating power in stationary plasmas. As far as both the central heating and the central particle source have to be strongly coupled, a strong constraint between the particle flux at the edge and the central heating power can be found which mainly depends on the ratio D_{11}^e/D_{11}^i. In terms of temperatures, a critical temperature for the edge region can roughly be estimated (mainly proportional to D_{11}^e/D_{11}^i and to the central temperature) which defines a transport barrier. For T exceeding this critical value, the outer particle flux is less than the central refuelling rate, and the outer density increases. Additional moderate anomalous heat conductivity (up to 1 m^2/s) or radiative losses (up to 3 MW) will amplify the problem.

In Fig. 5, the time evolution of density and particle flux is shown for such a plasma (refuelling: 15×10^{20} s^{-1}; n: 10^{20} m^{-3}; T: 1 keV; P: 10 MW). At the beginning, the whole refuelling rate is balanced by particle losses. The transport barrier which occurs at about 100 milliseconds reduces the particle losses to nearly two third of the central filling rate.

The ratio of both transport coefficients depends, in principle, on the magnetic configuration. Hence, in W7-X this problem can be analyzed by varying the toroidal mirror term over a wide range.

References

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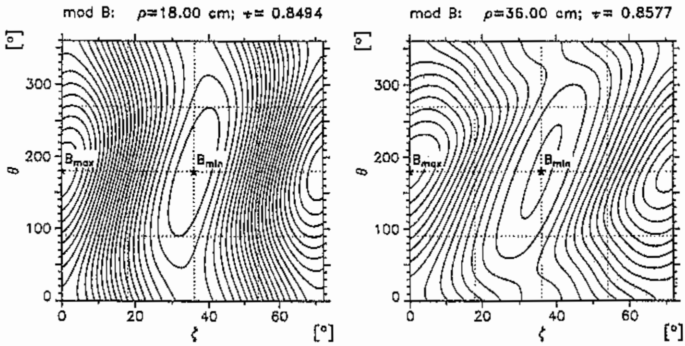

Fig. 1: Magnetic field topology of the W7-X high mirror configuration [6] at two radii with ζ and Θ being the toroidal and poloidal angle.

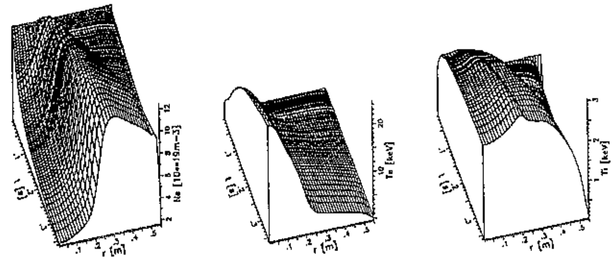

Fig. 2: Density and temperatures of a discharge with low particle refuelling rate ($P = 10$ MW).

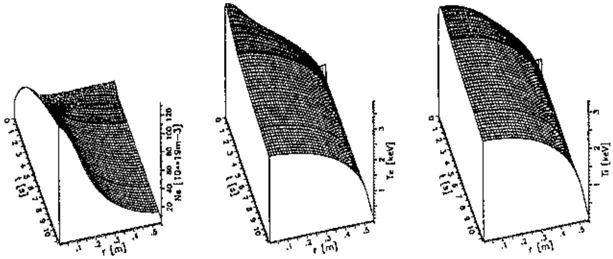

Fig. 3: Density and temperatures of a discharge with high particle refuelling rate ($P = 10$ MW).

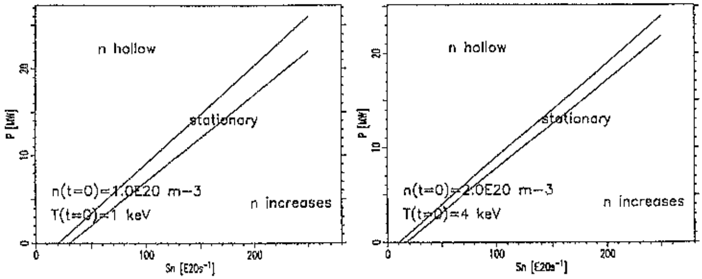

Fig. 4: Operational regimes for different heating powers and refuelling rates.

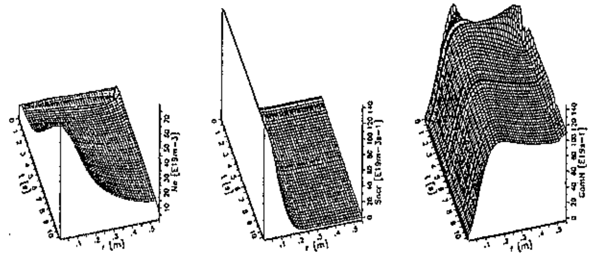

Fig. 5: Time evolution of density (left), particle source (middle) and particle flux (right) for a discharge with occuring transport barrier.