PARTICLE BALANCE IN NEUTRAL-BEAM-HEATED TOKAMAK PLASMAS

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ABSTRACT: The particle balance in H discharges in ASDEX during the steady-state ohmic and H phases is investigated by means of transport simulations. Profiles of particle sources and outward and inward flux densities are computed. The magnitude and radial extent of the sources due to cold atoms and beam fuelling and the corresponding convective energy loss are determined. It is further shown that the measured density profiles are not invariant to changes in particle source and confinement. Constraints on the electron heat diffusivity, the diffusion coefficient and the inward drift velocity are derived. An expression representing a lower limit for the diffusion coefficient in the presence of particle sources and inward fluxes is given.

Introduction: From the steady-state energy and particle balance equations with neutral injection it is possible to derive constraints on the electron heat diffusivity χ_e, the diffusion coefficient D and the inward drift velocity v_{in} /1/. Such relations are used to develop scaling laws and are applied in transport simulations. One prerequisite for such studies is to know the radial extent of the particle and energy sources due to neutral injection and the corresponding convective energy losses. The paper deals with the particle sources, particle confinement and resulting constraints for transport coefficients in injection-heated plasmas. The topical question of density profile invariance with changing particle sources is studied. Results from transport simulations with modified versions of the BALDUR code /2, 3/ are used. The neutral-gas transport is calculated by a Monte Carlo code. The particle source due to neutral injection is treated by following the fast neutrals by means of a Monte Carlo code.

Steady-state particle balance: Several discharges exhibiting long plateaus of current, density and beta were analysed. The example shown in Fig. 1 is an H discharge with I_p = 380 kA, $\bar{n}_e = 3.5\times10^{13}$ cm^{-3}, B_t = 2.15 T and P_{NI} = 3.45 MW ($H^o \rightarrow D^+$, E_o = 40 keV). The computations are compared with measured density and electron temperature profiles and with $\beta_{p\perp}$ from the diamagnetic loop. Good agreement is obtained by applying the coefficients /4, 5/

$$\chi_e^{OH}(r) = 1.6\times10^{16} A_i^{-1/2} B_t n_e(r)^{-1} T_e(r)^{-1} q(r)^{-1} \text{ cm}^2 \text{ s}^{-1} \quad (1)$$

$$D^{OH}(r) = 0.4 \ \chi_e^{OH}(r) \quad (2)$$

in the ohmic phase and

$$\chi_e^{H}(r) = 2.6\times10^{6} \ r_n(r)^{-1} q_a B_t(R_o)^{-1} \text{ cm}^2 \text{ s}^{-1} \quad (3)$$

$$D^{H}(r) = 0.4 \ \chi_e^{H}(r) \quad (4)$$

in the H phase. The inward drift velocity is given by $v_{in}(r) = 0.5\ D(r)\ r_{Te}(r)^{-1}$ cm s^{-1}, and the ion heat diffusivity used is three times the neoclassical values according to Chang and Hinton. The ion mass number is denoted by A_i. The toroidal magnetic field B_t is in kG, n_e is in cm^{-3}, T_e is in keV, q_a is the cylindrical q at the plasma radius a=40 cm and R_o = 167 cm is the major radius of the plasma. The quantities $r_n = -n_e/(\partial n_e/\partial r)$ and $r_{Te} = -T_e/(\partial T_e/\partial r)$ are in cm.

Under steady-state conditions the particle balance with anomalous outward diffusion and anomalous inward drift reads

$$-D \frac{dn_e}{dr} - v_{in} n_e = \Gamma_i + \Gamma_b \qquad (5)$$

where Γ_i and Γ_b are the flux densities due to the ionisation of cold atoms and due to the beam fuelling, respectively. The particle balance in the ohmic phase is shown in Fig. 2. Since the plasma is impermeable to cold neutrals ($\lambda_o \ll a$ with mean free path λ_o), the interior of the plasma is almost source-free. This gives rise to nearly equal outward and inward fluxes, the typical difference being only 10 % of each of these fluxes. Obviously, the main contribution due to Γ_i occurs outside $r \approx 0.8$ a. The detailed Γ_i profile is given in Fig. 3.

Results from transport analysis of the H phase are presented in Fig. 4. It should be mentioned that almost identical results are obtained in L discharges. In contrast to the ohmic phase, the outward flux clearly exceeds the inward flux. For $r \lesssim 0.7$ a the dominant source is due to beam fuelling, while Γ_i still prevails in the edge region. As can be seen, at r= a/2 one obtains $v_{in}\, n_e \approx \Gamma_b \approx -0.5\, D\, dn_e/dr$. Figure 5 represents a detailed plot of $\Gamma_b(r)$. Comparison with the energy flux density $P_b(r)$ shows that the average energy per absorbed particle $\bar{E} = P_b(r)/\Gamma_b(r) = 23.8$ keV only varies by ±0.6 keV over the whole cross-section, so that to very good approximation P_b can be set proportional to Γ_b everywhere.

In ohmic plasmas the convective power loss is only significant in the edge region, where Γ_i is large. With neutral injection, however, high convective losses $P_c \approx 2.5\,(T_e+T_i)\,\Gamma_b$ also occur in the plasma bulk owing to the large particle source and high temperatures. The ratio $P_c/P_b \approx 2.5\,(T_e+T_i)/\bar{E}$ amounts to about 30 % at r=2a/3. With increasing heating power the fraction of P_b lost by convection grows with the temperature sum to unacceptably high values, unless E_o and $\bar{E}$ are correspondingly raised.

The response of the density profile shape to changes in the particle source distribution is demonstrated in Fig. 6. During the ohmic phase the measured density profile is parabolic, while it is more triangle-shaped in the H phase. Evidently, the density profile shape is not invariant to changes in particle source and confinement.

Constraints on transport coefficients with injection heating: General expressions for transport coefficients are derived from approximate particle and energy balance equations. Using $\Gamma_i \ll \Gamma_b$ for $r \lesssim 0.7$ a in Eq. (5) yields

$$\frac{v_{in}}{D} \simeq r_n^{-1} - \frac{\Gamma_b}{n_e D} \qquad (6)$$

Unlike in the source-free case ($v_{in}/D = r_n^{-1}$), the ratio v_{in}/D is here determined by the beam-fuelling profile as well, which has to be taken from code calculations. To avoid this disadvantage, we eliminate Γ_b with the help of the energy balance.

For $r \lesssim 0.7$ a the losses due to charge exchange and radiation are negligibly small. At injection powers much higher than the ohmic input and negligible ion heat conduction one obtains

$q_e(r) = P_b(r) - P_c(r)$ (7)

where q_e is the flux density due to electron heat conduction. With $P_b(r) = \bar{E}\Gamma_b(r)$ and $P_c = 2.5\ (T_e+T_i)\ \Gamma_b$ it follows that

$$\Gamma_b = -[\bar{E} - 2.5(T_e+T_i)]^{-1}\ n_e\chi_e \frac{dT_e}{dr} \qquad (8)$$

Replacing the particle source in Eq. (6) yields

$$\frac{v_{in}}{D} \approx r_n^{-1} + [\bar{E}-2.5(T_e + T_i)]^{-1} \frac{\chi_e}{D} \frac{dT_e}{dr} \qquad (9)$$

This relation holds under stationary conditions for $P_{OH} \ll P_{NI}$ and $\Gamma_i \ll \Gamma_b$. An even simpler formula is obtained by setting χ_e/D equal to a constant. It was shown above that $\bar{E}$ is a constant which is usually large compared with the temperature sum. The ratio v_{in}/D can be determined from measured density and temperature profiles without knowing the beam-fuelling source. Using, for instance, the approximations $n_e(r) = n_e(0)\ (1-r/a_1)$ and $T_e(r) = T_e(0)\ (1-r/a_2)$ yields $v_{in}/D = (a_1-r)^{-1}$ - const, i.e. the increase of v_{in} with radius is much stronger than that of D.

The weak radial dependence of $P_b = \bar{E}\Gamma_b$ in the range $0.25 \leq r/a \leq 1$ (see Fig. 5) results in $q_e = -n_e\chi_e dT_e/dr \approx$ const (see Eq. (7)). With the above T_e profile one thus obtains $\kappa_e = n_e\chi_e \approx$ const and $D(r) \sim \chi_e(r) \sim n_e(r)^{-1}$.

According to Eq. (5) the diffusion coefficient reads $D = -(\Gamma_i+\Gamma_b+v_{in}n_e)/(dn_e/dr)$. In the case $v_{in}=0$ one obtains the expression

$$D(r) = - \frac{\Gamma_i(r) + \Gamma_b(r)}{\frac{dn_e}{dr}(r)} \qquad (10)$$

which represents a lower limit, since for given particle sources and density profile a finite inward flux always corresponds to a higher diffusion coefficient. The minimum D can also be given when the anomalous inward flux is unknown. Equation (10) is especially useful for predictive code simulations, because it yields the minimum D values which are able to produce the measured density gradients.

References

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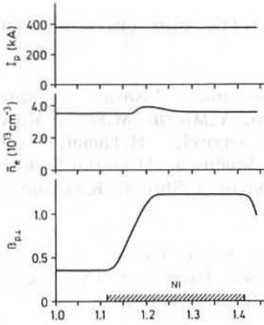

Fig. 1: Time evolution of plasma current, line-averaged density and poloidal beta in an H discharge.

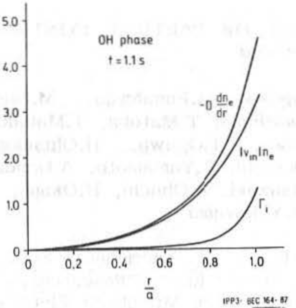

Fig. 2: Particle balance in the steady-state ohmic phase.

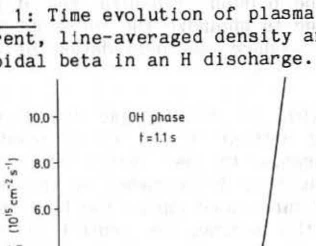

Fig. 3: Γ_i profile in the ohmic phase.

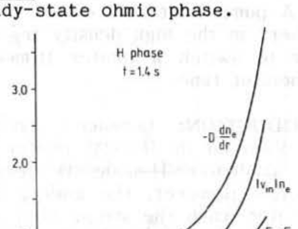

Fig. 4: Particle balance in the steady-state H phase.

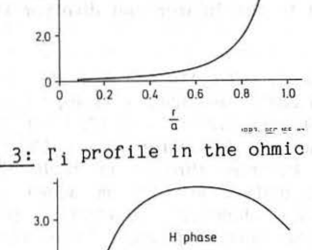

Fig. 5: Γ_b profile in the H phase.

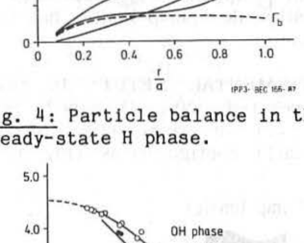

Fig. 6: Density profiles with ohmic heating and neutral-beam injection.