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Overview on the Radial Electric Field, Plasma Rotation and Transport in the Stellarator W7-AS

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Abstract

In the advanced stellarator W7-AS the radial electric field E_r is measured by active charge exchange recombination spectroscopy CXRS. In parallel, it is calculated by using the neoclassical DKES code. A comparison of calculated and measured solutions reveals in how far the neoclassical model is valid for the description of the radial particle transport and the formation of E_r. In general good consistency is found, even for the outer radii where the neoclassical fluxes become much smaller than the experimental ones. In this paper the interplay between the particular E_r roots and transport is considered. For strongly positive E_r a reduction of χ_e is observed in the vicinity of the magnetic axis. The typically negative ion-root in the gradient region strongly influences the local ∇T_i, thus determining the maximum attainable $T_i(0)$.

Keywords:

radial electric field, spectroscopy, neoclassical transport, W7-AS, ion root, electron root

1. Introduction

Stellarators suffer, in comparison to tokamaks, from enhanced neoclassical transport especially in the long mean free path LMFP regime. There, large populations of trapped particles are subject to drift losses. This unfavourable effect is partly compensated by the so-called optimization procedure [1], where the magnetic configuration is tailored in such a manner that those drifts are minimized. Another reduction of radial losses in the LMFP occurs as a consequence of a radial electric field E_r which develops in accordance to the ambipolarity condition:

$$\Gamma_e(r, E_r) + \Gamma_i(r, E_r) + Z_I \Gamma_I(r, E_r) = 0 \qquad (1)$$

Following neoclassical theory, the radial particle fluxes Γ and heat fluxes Q are functions of E_r [2]:

$$\Gamma_\alpha = -n_\alpha \left\{ D_{11}^\alpha \left(\frac{n'_\alpha}{n_\alpha} - \frac{eZ_\alpha E_r}{T_\alpha} \right) + D_{12}^\alpha \frac{T'_\alpha}{T_\alpha} \right\} \qquad (2.1)$$

$$Q_\alpha = -n_\alpha T_\alpha \left\{ D_{21}^\alpha \left(\frac{n'_\alpha}{n_\alpha} - \frac{eZ_\alpha E_r}{T_\alpha} \right) + D_{22}^\alpha \frac{T'_\alpha}{T_\alpha} \right\} \qquad (2.2)$$

In LMFP, the transport coefficients $D_{ij}^\alpha(E_r)$ for electrons α = e and ions α = i are reduced, in the plateau regime only those of the ions. Z is the charge, n the density, T the temperature. A possible Ware-pinch contribution in Eq. (2.1) proportional to D_{13} is neglected, because $E_\parallel$ is very small as a consequence of the net current free stellarator operation. To calculate the neoclassical E_r, the DKES code [3] is used which takes into account the complex magnetic configuration of W7-AS. Starting from a Fourier representation of the magnetic field, DKES calculates the monoenergetic transport coefficients D_{ij}^α to solve Eq. (1). These solutions are the neoclassical roots of the ambipolar E_r. The most positive is referred to as electron-root, the most negative as ion-root, solutions between them are

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not stable. The total number of all roots is always odd [4]. DKES, however, might fail in the estimation of Γ_i for very strong E_r, because in that case variations of n_I and the electrostatic potential on flux surfaces might appear which are not taken into account. The strongly positive electron-root should be accessible for the case that the electrons are in the LMFP, and the condition $\Gamma_e(E_r = 0) \gg \Gamma_i(E_r = 0)$ holds. This is typically the case in W7-AS for low $n_e(0) < 3 \times 10^{19}$ m^{-3} and high T_e. For higher $n_e(0)$ only the ion-root is expected with $\Gamma_e(E_r = 0) \ll \Gamma_i(E_r = 0)$. It is characterized by small negative values near the magnetic axis and strongly negative values in the gradient region.

Charge exchange recombination spectroscopy CXRS [6] in a modulated diagnostic neutral beam is used in W7-AS [7] to determine radial profiles of the toroidal and poloidal rotation velocity V [5]. From the simplified radial force balance [8]:

$$E_r = \frac{\partial(n_{I+1}(r)\cdot T_{I+1}(r))}{\partial r}\cdot\frac{1}{eZ_{I+1}n_{I+1}(r)} + \frac{T_I(r)\gamma}{eZ_{I+1}}\cdot\frac{\partial\zeta_I/\partial r}{\zeta_I} + (B_\theta V_\varphi - B_\varphi V_\theta) \qquad (3)$$

the radial electric field profile $E_r(r)$ is determined. CXRS also provides the impurity density $n_I(r)$ and ion temperature $T_I(r)$ after CX which changes Z from $I+1$ to I. $\boldsymbol{B}$ is the magnetic field, ζ the electronic state excitation probability, e the electron charge. With the ion gyro-frequency ω and the mean excited state lifetime τ we define $\gamma = (\omega\tau)^2/\{1 + (\omega\tau)^2\}$. In general it is found that the major contribution to E_r comes from the poloidal rotation (50% − 80%). V_θ dominates because of the relatively small magnetic pumping due to the large aspect ratio, and because of the small mean ∇B as a consequence of the optimization procedure. Only a minor contribution comes from the ion diamagnetic pressure term (15% − 45%). V_φ typically contributes to less than 5%, because $B_\theta V_\varphi \ll B_\varphi V_\theta$. Furthermore, the toroidal viscous damping caused by collisions between passing and trapped particles is very large due to the missing axi-symmetry. A fast toroidal rotation is found only in discharges with non-balanced neutral beam heating NBI, but even then its contribution to E_r is negligible. The value of V_φ is described well by neoclassical toroidal viscosity [9]. The comparison of neoclassical and measured E_r is also a sensitive test in how

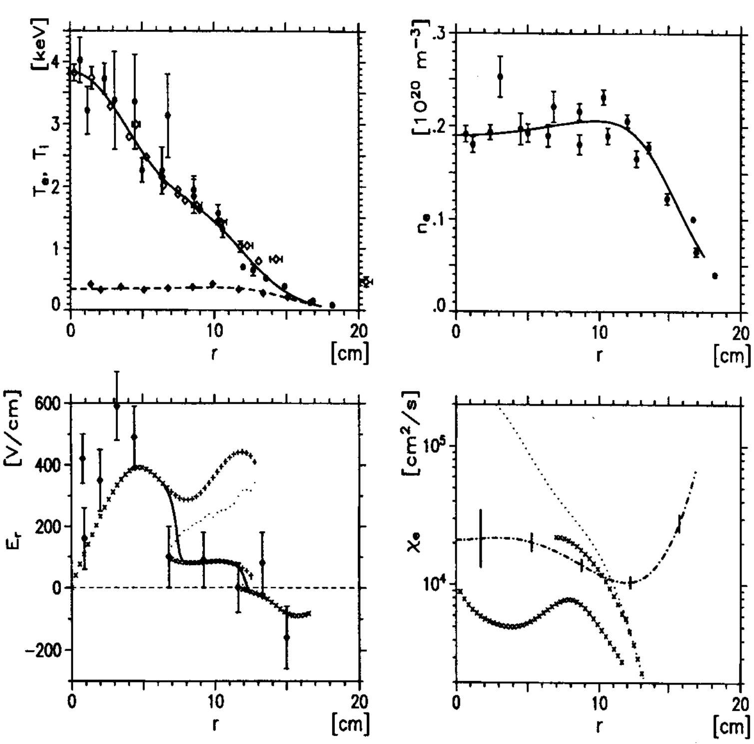

Fig. 1 Upper left: electron (solid) + ion (broken) temperature; upper right : electron density; lower left: E_r from CXRS (dots), from DKES: stable roots (crosses), unstable solution (dots); lower right: experimental χ_e (dot-dashed), neoclassical for stable roots (crosses), for $E_r = 0$ (dots).

far possible anomalous fluxes near the plasma edge are intrinsically ambipolar.

2. Electron Root

For a stellarator reactor, a starting scenario in the electron-root is considered [10]. In particular, for this case in Eq. (2.1) the positive linear E_r term dominates [2], thus leading to an enhanced outward drift of impurities. Accumulation of impurities, especially of the Helium ash, could thus be prevented. In W7-AS in fact hollow He^{++} density profiles are measured [11] for positive E_r. Figure 1 shows W7-AS profiles for a discharge with an E_r profile resembling the neoclassical electron-root. This is a low density discharge at high on-axis electron cyclotron heating ECRH power (770 kW 2nd harmonic 140 GHz X-mode). A strong positive E_r develops near the plasma axis, leading to a considerable reduction of the central χ_e, as revealed by the experimental power balance analysis. Thus a maximum $T_e(0)$ up to 4 keV is obtained, the largest measured so far in W7-AS. The appearance of the strongly positive E_r is accompanied by a local increase of $\nabla T_e(r \cong 3$ cm), directly indicating the locally reduced electron heat transport. That local transport reduction can be seen in the plot on the lower right, where the experimental χ_e near the plasma center comes closer to the neoclassically expected one from DKES for the E_r electron-root solution than for $E_r = 0$. The measured E_r from CXRS and the neoclassically calculated agree well. For higher $n_e(0)$ or reduced heating power the central positive E_r disappears. It also disappears for the case that the local B-field minimum in the ECRH launching plane is removed by modifications of the magnetic configuration, or by shifting the ECRH power deposition from on-axis away towards off-axis [14]. It is assumed that drifts of ripple trapped suprathermal electrons in the ECRH launching plane contribute strongly to the radial electrons fluxes, additionally to the thermal ones. This is supported by the much faster temporal decay of the central T_e in comparison to the outer T_e after switching off the ECRH power at the end of the discharge.

3. Ion Root

The second discharge, shown in Fig.2, is characterized by combined ECRH (750 kW at 140 GHz) +

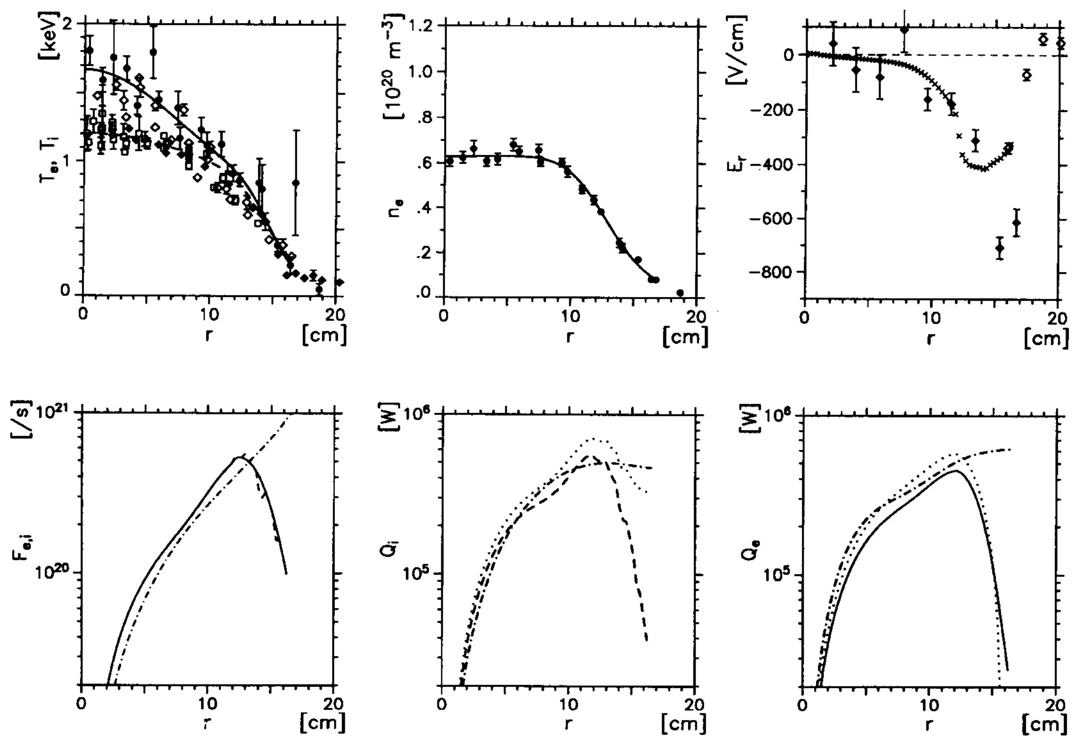

Fig. 2 Upper left: electron (solid) + ion (broken) temperature; upper middle: electron density; upper right: E_r from CXRS (dots), from DKES (crosses); lower left: particle fluxes from DKES (solid) and experimental (dot-dashed); lower middle: neoclassical ion heat fluxes (dotted + dashed), from power balance (dot-dashed); lower right: neoclassical electron heat fluxes (solid + dotted), from power balance (dot-dashed).

neutral beam NBI (680 kW absorbed) high heating power at medium $n_e(0) \approx 6 \times 10^{19}$ m^{-3}. Typically, only the ion-root solution establishes for this type of discharge. The values for E_r and $\nabla T_i(r \cong 14$ cm) shown in this example are the largest observed in W7-AS so far. As a result of the steep ∇T_i, $T_i(0)$ reaches maximum values. Up to 1.5 keV are found [16]. The strong E_r in the gradient region might act as a potential barrier for the ions, coupling the ion heat fluxes strongly to the electron ones. The transport analysis reveals that both heat and particle fluxes are described well by neoclassical theory, at least up to about 12 cm. The central particle fluxes are well consistent with the values obtained from FAFNER [12] code calculations. Further outside, recycling neutral gas from the vessel wall provides an additional particle source increasing locally the anomalous particle fluxes. These fluxes contribute strongly to the convective heat fluxes, therefore higher particle sources in the gradient region could limit the maximum attainable $\nabla T_i(r \cong 14$ cm) and $T_i(0)$ as well as the maximum E_r for the total heating power available. That critical limit, however, is not yet reached for the discharge shown. Sufficiently low neutral particle sources in the gradient region seem to be the pre-requisite to obtain these strong E_r in conjunction with maximum $T_i(0)$. Furthermore, the experimental energy confinement time τ_E exceeds the prediction from the ISS95 regression database [13] for W7-AS by roughly a factor of two. That might, to some extent, also be due to the strongly sheared poloidal rotation in the gradient region, leading to a reduction of the correlation length of electron density fluctuations [17], thus reducing the turbulent anomalous transport. The reason for the deviation between measured and calculated E_r near the plasma periphery is subject to further investigations. Several mechanisms as fast ion orbit losses, helical resonances, non-ambipolar CX ion fluxes are quantitatively considered but found not to be sufficient as explanation [15]. The DKES ordering, however, might fail for these strong E_r. It is emphasized that the deviation shown is not at all typical for W7-AS: about 40 discharges have been investigated so far and good agreement is found (also in that radial range). That holds even when the neoclassical particle fluxes are much smaller than the experimental ones. Therefore we conclude that any anomalous fluxes seem to be intrinsically ambipolar.

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