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Transport Analysis in Low-Collisionality W7-AS Plasmas

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Abstract

At W7-AS, the confinement properties are analyzed and compared mainly with neoclassical predictions for quite different conditions. Low density ECRH discharges allow access to the very long mean free path regime for electrons (T_e up to 4 keV at $n_e \simeq 1 - 2\times10^{19}$ m^{-3}) whereas combined NBI/ECRH discharges at high density ($T_e \approx T_i > 1$ keV at $n_e \simeq 10^{20}$ m^{-3}) lead to high performance. Depending on the achieved temperatures, the experimental transport analysis in the plasma core is consistent with the neoclassical predictions. The experimentally observed "electron root" feature with strong $E_r > 0$ is driven by the ECRH at high power levels. The neoclassical prediction of a purely thermal "electron root" is not supported experimentally. The standard neoclassical ordering scheme is violated for ions in case of very strong E_r.

Keywords:

W7-AS, neoclassical transport, DKES code, strong radial electric field, ECRH-driven electron root, self-consistent neoclassical approach

1. Introduction

High temperatures are most important for the transport analysis in the stellarator long-mean-free-path (*lmfp*) regime. For these conditions, neoclassical theory predicts an unfavourable dependence of the transport coefficients on temperature. Thus, the transport analysis in low-collisionality plasmas is best suited for the examination of the neoclassical predictions. With respect to future large stellarators, neoclassical theory seems to be a fairly reliable tool which may be used for predictive transport codes.

Close to the plasma edge at low temperatures, neoclassical theory fails. The confinement in this region is dominated by *anomalous* transport (*i.e.*, the physics are not yet understood). Especially in W7-AS with the fairly low vacuum shear, the confinement properties depend sensitively both on the value of the rotational transform (low order rational values of ι can lead to confinement degradation) and on the shear, $d\iota/dr$ (the shear in the $E\times B$ rotation may also play a role). However, this paper concentrates on the confinement properties in the bulk plasma for optimum conditions.

2. Optimum Confinement Discharges

In high power NBI/ECRH discharges, a narrow density profile allows steep temperature gradients (and large $E_r < 0$) close to the plasma edge where n_e becomes very small. For this type of discharges, optimum confinement properties are found ($T_e > T_i \simeq 1.5$ keV) with τ_E exceeding the sc ISS95 scaling [1] by at least a factor of 2. The experimental particle fluxes as well as the ion and electron energy fluxes are in good agreement with

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the neoclassical predictions up to 70% of the plasma radius; see Refs. [2]. Furthermore, the predicted E_r obtained from the ambipolarity condition of the neoclassical fluxes is consistent with the experimental findings [3] also at the outer radii where the ambipolar neoclassical fluxes become very small. These findings indicate that the additional *anomalous* particle fluxes may be intrinsically ambipolar.

Good wall conditioning and very low recycling are mandatory to obtain the narrow density profiles and to provide global density control even for high NBI power levels (with a particle source strength of up to 2.5×10^{20} /s). Contrary to NBI discharges in the "early phase" of W7-AS operation, the n_e profiles are fairly narrow, and the edge density is very low. Moreover, the outer density profile is — within the experimental errors — independent of both the central density and the heating power. This very surprising result is shown in Fig. 1. Here, the T_e gradient at the outer radii reflects the heating power. Furthermore, $T_i \simeq T_e$ is found in this region [3]. The steep temperature gradients flatten in the bulk region due to the strong temperature dependence of the neoclassical transport coefficients leading to the optimum confinement in this type of discharges.

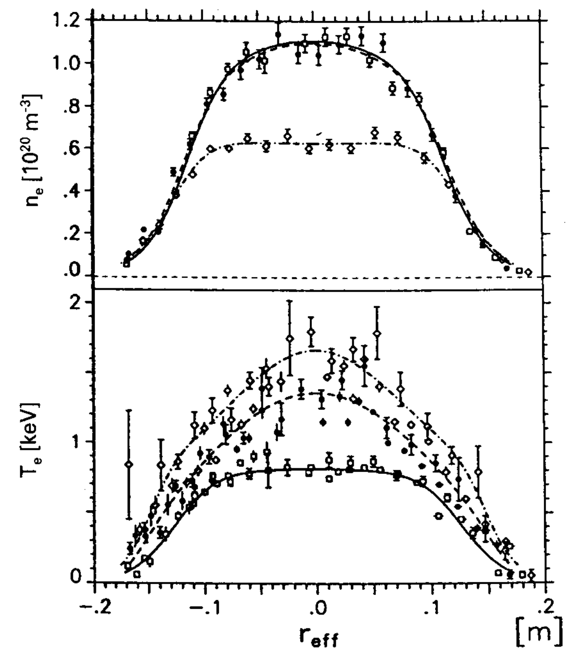

Fig. 1 Electron density and temperature profiles for optimum confinement conditions at different density and heating power solid line: 450 kW NBI; dashed line: 1650 kW and dot-dashed line: 2100 kW both with combined NBI/ECRH).

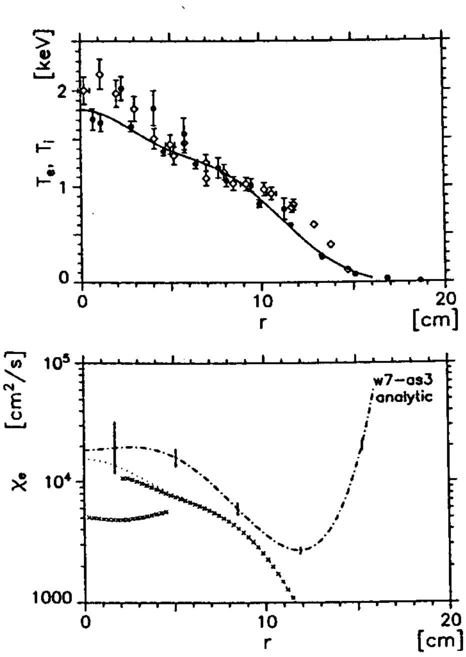

Fig. 2 The electron temperature profile (upper plot) and the electron heat diffusivity for an ECRH discharge (~400 kW at 140 GHz 2nd harmonic X-mode) with optimum confinement (25 kA plasma current) at moderate density ($n_e(0) \simeq 4\cdot10^{19}$ m^{-3}): • from Thomson scattering and ◇ from ECE; The experimental χ_e (from power balance, dot-dashed line) and the neoclassical predictions (lower plot, the dotted line is for $E_r = 0$). Here, the predicted "electron root" ($r<5$ cm) is experimentally not indicated.

Also in ECRH discharges at moderate density, the achieved electron temperatures are limited by neoclassical transport in the bulk region. An example with optimized edge confinement at high magnetic shear (ι') by a plasma current of 25 kA is shown in Fig. 2; see [4]. The evaluation of the electron heat diffusivity — both the experimental one from power balance and the neoclassical one — are based on the T_e data from Thomson scattering, the ECE data indicate even better edge confinement (the high plasma current was taken into account in the equilibrium calculations of the magnetic coordinate transformation). With this uncertainty, the electron energy flux is in agreement with the neoclassical prediction within 70% of the plasma radius.

3. ECRH Driven "Electron Root" Feature

Strongly positive radial electric fields have been measured at W7-AS in low density discharges at high ECRH power level. The electron temperature profiles are highly peaked (with $T_e(0)$ up to 4 keV), whereas the ion temperature and the density profiles are flat.

The finding of the strongly positive E_r is related to an additional peaking of the central T_e profile indicating improved electron energy confinement. The corresponding experimental χ_e is much lower than the neoclassical one for $E_r \simeq 0$. This "electron root" feature at sufficient ECRH power is only found for W7-AS configurations where a significant fraction of the ECRH power at 2nd harmonic X-mode is absorbed by ripple-trapped electrons close to the magnetic axis. Equivalent experiments in a configuration without trapped electrons in the ECRH launching plane show neither these strongly positive E_r nor the additional peaking of the T_e profile. The transient response of the central T_e in case of ECRH power modulation or switch-off strongly indicates that the ECRH driven electron flux is responsible for this "electron root" feature; see Fig. 3. For the configuration with an enhanced minimum of the magnetic field strength in the ECRH launching plane, the central T_e is higher than in the neoclassically improved configuration (with a maximum of B), however, this additional peaking in the central T_e disappears within less than 1 ms after the ECRH is switched off. Furthermore, the temperature decay is significantly faster than is measured for the improved configuration confirming directly the neoclassical prediction.

The evidence, that ripple-trapped suprathermal electrons generated by the ECRH contribute to the ambipolarity condition of the particle fluxes, is supported by Monte Carlo simulations [5] (in 5D phase space). At intermediate radii, slightly positive E_r ("ion root" for $T_e \gg T_i$) are predicted for "purely" thermal particle fluxes which are consistent with the experimental data. Also the experimental heat diffusivity (from power balance) is in good agreement with the neoclassical one. In the region of the "electron root" feature, however, the strongly positive E_r reduce the thermal neoclassical electron fluxes, but also the ion ones are so strongly decreased that the suprathermal ECRH driven fluxes cannot be balanced. In the conventional neoclassical theory, the ion transport coefficients in the *lmfp* regime decrease at least with $E_r^{-3/2}$. Consequently, this approach must be reviewed for the case of strong E_r.

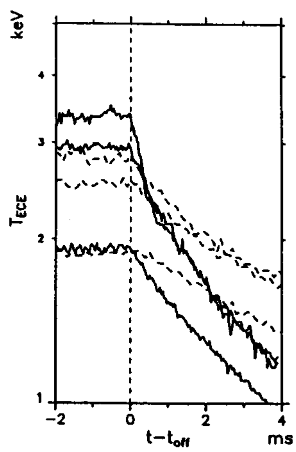

Fig. 3 Time traces of central ECE temperatures after the ECRH is switched off for equivalent discharges in different magnetic configurations with ripple-trapped particles in the ECRH launching plane (solid lines) and without (dashed lines).

4. Need of Self-Consistent Neoclassical Theory

The strongly positive radial electric field within the region of the "electron root" feature leads to complex effects on the flux surfaces. In the continuity equation, the inhomogeneity of B with $\nabla \cdot \boldsymbol{v}_{E\times B} \simeq -2\boldsymbol{v}_{E\times B} \cdot \nabla \ln B$ drives a parallel flow (which is the equivalent of the Pfirsch-Schlüter current) as well as a (1st order) density inhomogeneity, n_1, which is linked to a (1st order) potential varying on flux surfaces. With respect to the "usual" neoclassical theory, a strong E_r leads also to modifications. For example, in the DKES code [6] the $E\times B$ drift is assumed to be constant on flux surfaces, and density inhomogeneities are neglected.

In the conventional neoclassical approach, the 0th order distribution function, f_0, must satisfy $C(f_0)=0$ with C being the Coulomb collision operator, *i.e.*, f_0 corresponds to the Maxwellian, $f_M(r,v^2)$, and the radial derivative drives the neoclassical transport in 1st order. This approach can be generalized to include the transport along the magnetic field lines due to small poloidal and toroidal electric fields on the flux surfaces, $-\nabla\Phi_1$, and the 0th order DKE is given by

$$v_{\parallel} \cdot \nabla f_0 + \dot{v}\,\frac{\partial f_0}{\partial v} = C(f_0) \qquad \text{which yields}$$

$$f_0 = e^{-\frac{q\Phi_1}{T}} f_M(f, v^2)\,.$$

Here, $\dot{v}$ is only the parallel acceleration term ($\propto p\boldsymbol{B} \cdot \nabla\Phi_1$ with the pitch, $p = v_{\parallel}/v$). The other contribution to $\dot{v}$ originating from the radial ∇B-drift in a strong radial electric field ($\propto (1+p^2)$, $(\boldsymbol{B} \times \nabla B) \cdot \nabla\Phi_0$) violates the isotropic ansatz for f_0, *i.e.*, $C(f_0) \neq 0$, and must be omitted in 0th order. It follows, that the poloidal $\boldsymbol{B} \times \nabla\Phi_0$ can be treated only in 1st order.

In the 1st order DKE, the terms related to $\partial f_1/\partial r$ and $\partial f_1/\partial v$ are neglected with respect to the equivalent terms in f_0, and the Coulomb term, C, is approximated by the simple pitch-angle collision operator. Then, r and v are only parameters in the 1st order "mono-energetic" DKE.

$$\left(\frac{pn}{B}\boldsymbol{B}+\boldsymbol{v}_{\nabla B}+\frac{1}{B^2}\boldsymbol{B}\times\nabla\Phi_0\right)\cdot\nabla f_1$$
$$-\frac{1-p^2}{2B}\left(\frac{2q}{mv}\boldsymbol{B}\cdot\nabla\Phi_1+\frac{v}{B}\boldsymbol{B}\cdot\nabla\boldsymbol{B}+\right.$$
$$\left.\frac{p}{B^2}(\boldsymbol{B}\times\nabla B)\cdot\nabla\Phi_0\right)\frac{\partial f_1}{\partial p}-C(f_1)$$
$$=-(\boldsymbol{v}_{\nabla B}+\boldsymbol{v}_{E_1\times B})_r f_0'$$

Here, f_0' is the radial derivative (under the constraint of invariant total energy) which drives all the neoclassical transport in combination with the radial components of $\boldsymbol{v}_{\nabla B}=(mv^2/2qB^3)\ (1+p^2)\ \boldsymbol{B}\times\nabla\boldsymbol{B}$ and $\boldsymbol{v}_{E_1\times B}=\boldsymbol{B}\times\nabla\Phi_1/B^2$, respectively.

The Fourier expansion (with respect to the toroidal and poloidal angles) of the 1st order DKE leads to mode coupling. In DKES, only the "mirror term" $\boldsymbol{B}\cdot\nabla B\partial f_1/\partial p$ is taken into account leading to the contribution of the ripple trapped particles which dominates in the *lmfp* regime. Both the $\boldsymbol{B}\cdot\nabla\Phi_1\partial f_1/\partial p$ and $(\boldsymbol{B}\times\nabla B)\cdot\nabla\Phi_0\partial f_1/\partial p$ terms lead to additional mode coupling ($\boldsymbol{v}_{E\times B}\cdot\nabla f_1$ and $\boldsymbol{v}_{\nabla B}\cdot\nabla f_1$ are of minor importance for mode coupling) and affect the *lmfp* transport as evaluated by DKES. In this way, a strong $E\times B$ rotation drives a 1st order density, n_1, and potential, Φ_1. As the $\boldsymbol{v}_{E\times B}$ is partly counteracted by the $\boldsymbol{v}_\parallel$ term (with respect to ∇f_1), the effect of poloidal rotation is much stronger in the ion drift-kinetic equation, whereas Φ_1 affects both equations. Finally, the radial electric field is determined from the ambipolarity condition of the particle fluxes and Φ_1 from the quasi-neutrality condition ($n^e=n^i$) on the flux surfaces.

In principle, this coupled system of drift-kinetic equations can be solved iteratively. The 1st order mono-energetic DKE is solved with Fourier expansion of B, f_1 and Φ_1 both for electrons and ions. By energy convolution, the 1st order densities are calculated, and Φ_1 from the Boltzmann factor in 0th order is estimated to satisfy the quasi-neutrality condition. A first attempt of integrating self-consistently this system of DKE's has already been performed [7].

Although no "convective" particle fluxes are driven by Φ_1 in 0th order (*i.e.*, with f_0), the energy flux is directly affected. With respect to f_1 (which leads to the conventional neoclassical transport), a strong E_r will modify the particle and energy transport both for electron and ions. In particular, the nearly vanishing ion transport coefficients for strong E_r as obtained from DKES may be substantially affected. Consequently, the prediction of a "purely neoclassical electron root" (typically obtained for low density ECRH discharges in W7-AS) without the drive of fast ripple trapped electrons generated by the ECRH seems to be unreliable.

Finally, this self-consistent approach seems to be essential for describing the impurity transport. The relative effect of the radial electric field scales with $\sqrt{m_I}$, and the impurity transport coefficients in the conventional approach can become much too small. Even in a "tracer" modelling, the 1st order potentials generated by the bulk ions may dominate the impurity transport. A simple impurity transport modelling was found to be inappropriate with respect to the W7-AS findings [8].

5. Conclusions

Neoclassical theory is confirmed by the experimental transport analysis in low-collisionality W7-AS plasmas, *i.e.*, in the bulk part at sufficiently high temperatures. This conclusion holds for the ion and electron heat conduction as well as for the particle transport. Also the predicted ambipolar electric field is consistent with experimental findings except when the strongly positive "electron root" is predicted. Based on purely thermal neoclassical particle fluxes, the ambipolarity condition typically predicts these strongly positive E_r ("electron root") in low density ECRH plasmas with highly peaked T_e profiles which is not consistent with the experimental findings. Only for special conditions, where a significant amount of the ECRH power is absorbed by ripple-trapped electrons, do the ECRH generated suprathermal electron fluxes lead to the strong $E_r>0$. In this sense, an ECRH driven "electron root" feature was found at W7-AS (with $T_e(0)$ up to 4 keV). However, a basic assumption of the conventional neoclassical theory is violated for the ions by these very large E_r. In the case of higher density, the radial electric fields are typically slightly negative allowing for the conventional neoclassical approach.

In a next step, however, a self-consistent neoclassical code, which takes also the density variations on flux surfaces into account, should be developed. Such a code seems to be mandatory to extend the neoclassical theory to the impurity transport in stellarators. So far, the neoclassical predictions for the impurity transport show an extremely sensitive dependence on the radial electric field; poloidal and toroidal electric fields (which are also responsible for the transport in the Pfirsch-Schlüter regime) are not taken into account. Since the impurity transport will likely be a crucial topic for future large stellarators, one should start with a self-consistent neoclassical description.

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