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 = 1 - 2x10¹⁰ m⁻³) whereas combined NBI/ECRH discharges at high density (T_e ≈ T_i > 1 keV at n_e = 10²⁰ 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_e > 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_i.

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 α can lead to confinement degradation) and on the shear, ds/dr (the shear in the E×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_i<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 = 1.5 keV) with T_i 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, 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 $2.5 \times 10^{20}/s$). 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, $T_e = T_i$ 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.

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 ($\psi'$) 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 $x_e$ is much lower than the neoclassical one for $E_r=0$. 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 bipolarity 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 \( \text{lmp} \) regime decrease at least with \( E_r^{-3/2} \). Consequently, this approach must be reviewed for the case of strong $E_r$.

### 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 \( V \cdot Y_{\text{EB}} = -2V_{\text{EB}} \cdot V \) in $B$ 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, $f_0(r,v^2)$, 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

$$ v_i \cdot \nabla f_0 + \frac{\partial f_0}{\partial v} = C(f_0) \quad \text{which yields} $$

$$ f_0 = e^{-\int_0^v} f_0(v, f(v)) \cdot $$

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

In the 1st order DKE, the terms related to $\partial f_0/\partial r$ and $\partial f_0/\partial v$ are neglected with respect to the equivalent terms in $f_0$, and the Coulomb term, $C$, is approximated

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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).
by the simple pitch-angle collision operator. Then, \( r \) and \( \nu \) are only parameters in the 1st order \("\text{mono-energetic}\) DKE.

\[
\left( \frac{P_n}{B} B + r_{\nu B} + \frac{1}{B^2} B \times \nabla \Phi_0 \right) \cdot \nabla f_1 \\
- \frac{1 - \nu^2}{2B} \left( \frac{2n}{m} B \cdot \nabla \Phi_1 + \frac{\nu}{B} B \cdot VB + \frac{P}{B^2} (B \times VB) \cdot \nabla \Phi_0 \right) \frac{df_1}{dp} = C(f_1) \\
- (r_{\nu B} + r_{Ei}B) \nabla \Phi_0 \cdot f_0
\]

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 \( r_{\nu B} = (n v^2 / 2 q B^2) (1 + \nu^2) B \times VB \) and \( r_{Ei}B = B \times \Phi_0 / B^2 \), 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 \("\text{mirror term}\) \( B \times VB \Phi_1 / \partial p \) is taken into account leading to the contribution of the ripple trapped particles which dominates in the \( limf \) regime. Both the \( B \cdot \nabla \Phi_1 \partial f_1 / \partial p \) and \( (B \times VB) \cdot \nabla \Phi_0 \partial f_1 / \partial p \) terms lead to additional mode coupling (\( \nu_{EB} \) and \( \nu_{VB} \) of \( f_1 \) are of minor importance for mode coupling) and affect the \( limf \) transport as evaluated by DKES. In this way, a strong \( E \times B \) rotation drives a 1st order density, \( n_1 \), and potential, \( \Phi_1 \). As the \( \nu_{EB} \) is partly counteracted by the \( \nu_{VB} \) term (with respect to \( \nabla f_1 \)), the effect of poloidal rotation is much stronger in the ion drift-kinetic equation, whereas \( \Phi_1 \) affects both equations. Finally, the radial electric field is determined from the ambipolarity condition of the particle fluxes and \( \Phi_1 \) from the quasi-neutrality condition \((n = n')\) 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 \( \Phi_1 \) both for electrons and ions. By energy convolution, the 1st order densities are calculated, and \( \Phi_1 \) 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 \("\text{convective}\) particle fluxes are driven by \( \Phi_1 \) 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 \( E_i \) will modify the particle and energy transport both for electrons and ions. In particular, the nearly vanishing ion transport coefficients for strong \( E_i \) as obtained from DKES may be substantially affected. Consequently, the prediction of a \("\text{purely neoclassical electron root}\) (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 \( 1 / m_i \), and the impurity transport coefficients in the conventional approach can become much too small. Even in a \("\text{tracer}\) 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 \("\text{electron root}\) is predicted. Based on purely thermal neoclassical particle fluxes, the ambipolarity condition typically predicts these strongly positive \( E_i \) \("\text{electron root}\) in low density ECRH plasmas with highly peaked \( T_i \) 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 \( E_i > 0 \). In this sense, an ECRH driven \("\text{electron root}\) feature was found at W7-AS (with \( T_i(0) \) up to 4 keV). However, a basic assumption of the conventional neoclassical theory is violated for the ions by these very large \( E_i \). 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.

References