The Neoclassical "Electron-Root" Feature in W7-AS

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Introduction: The confinement properties of stellarators in the long mean free path regime are determined by the radial component of the ∇B-drift of particles trapped in local ripples. In the worst case, the unfavourable neoclassical temperature dependence of the heat flux, $q \propto T^{9/2}$, leads to rather poor confinement properties. Optimisation of the magnetic configuration - e.g., as performed for W7-X - can significantly reduce the averaged radial drift of these localized particles leading to an essential confinement improvement. A sufficiently strong radial electric field (the poloidal $E \times B$-drift) will force the trapped particle orbits close to the flux surfaces also leading to significantly reduced transport. With the neoclassical transport coefficients in the *lmfp* regime depending on E_r, multiple roots of the ambipolarity condition, $\Gamma_e = Z_i \Gamma_i$, may exist: the "ion root" solution with weak E_r for which only the ion transport coefficients are reduced, and the "electron root" solution at strongly positive E_r with additionally improved electron confinement. For classical stellarators (without optimisation of the magnetic configuration) the "electron root" scenarios are mandatory to obtain acceptable confinement properties. Furthermore, operation with the positive E_r may turn out to be essential for preventing neoclassical impurity accumulation.

Experimental Findings: Recently, strongly positive radial electric fields have been measured at W7-AS in low density discharges at high ECRH power level (≥ 400 kW) with 2nd harmonic X-mode (140 GHz). The electron temperature profiles are highly peaked (with $T_e(0)$ up to 4 keV), and the ion temperatures (with T_i of several 100 eV) fairly flat, see Fig. 1. The density profiles are flat or even slightly hollow. 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 heat diffusivity, χ_e , from the power balance is much lower than the neoclassical one for $E_r \simeq 0$. E_r simulations based on the neoclassical ambipolarity condition with only thermal fluxes taken into account predict only the "electron root" in the inner plasma region. The predicted neoclassical χ_e with these E_r are, however, smaller than the experimental ones.

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. For 70 GHz O-mode launching, an "electron root" feature was not observed, so far [1]. Equivalent experiments in a configuration without trapped electrons in the ECRH launching plane neither show these strongly positive E_r nor the additional peaking of the T_e profile. In spite of the fact that this specific magnetic configuration is neoclassically improved, the central T_e are lower than the ones of the "electron root" feature at equivalent power levels. A strong indication, that the ECRH driven electron flux (related to the generation of suprathermal electrons as shown by bounce-averaged Fokker-Planck calculations [2]) is responsible for the "electron root" feature, is found from the ECE temperature measurements after the ECRH is switched off, see Fig. 2. For the configuration with significant trapped particles in the launching plane (even more than in the "standard" configuration of Fig. 1), the decay of the central T_e is characterized by two different time scales. After a very fast decay (within less than 1 ms immediately after switch-off), the central T_e relaxes on a time scale similar to that slightly outside of the "electron root" region. For the "neoclassically improved" configuration, the initial fast decay is not found, and the central T_e is lower although the confinement (reflected by the time scale of $T_e(r,t)$) is clearly higher. Furthermore, the confinement

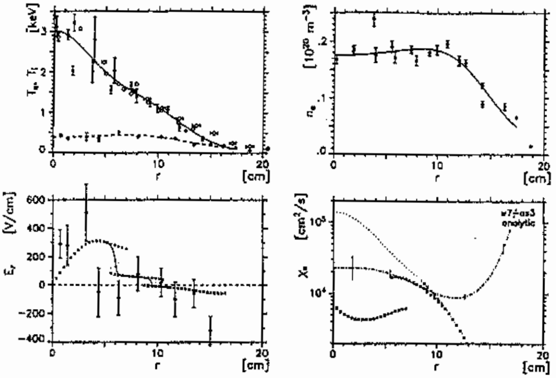

Fig. 1 *Temperature and density profiles for an ECRH discharge (X-mode at 140 GHz with 400 kW) in the W7-AS "standard" configuration. The E_r profile is simulated by means of the ambipolarity condition with only the thermal neoclassical fluxes taken into account (experimental E_r data from active CXRS, lower left plot). The electron heat diffusivities (lower right plot): the neoclassical ones with the simulated E_r (×), and with $E_r = 0$ (dotted line); the χ_e from power balance (dot-dashed line) is given for reference.*

properties of high energetic electrons found in the strongly down-shifted ECE channels (with small reabsorption by the plasma at outer radii on low-field side) also show the fast response, depending on the magnetic configuration.

Monte Carlo Simulations: The "convective" contribution of the ECRH driven electron flux is estimated by Monte-Carlo simulations in 5D phase space [3]. The quasi-linear diffusion term describing the ECRH in the Fokker-Planck equation is approximated by an explicit source term, $\underline{\nabla}_v \cdot \left(\underline{\underline{D}} \cdot \underline{\nabla}_v f_{\mathrm{Max}}\right)$. The quasi-linear diffusion coefficient, $D_{\perp\perp}(v_\parallel, v_\perp)$, is obtained from ray-tracing calculations for the different heating scenarios. In this linear approach, the driven electron flux is proportional to the heating power. Quasi-linear degradation effects at higher ECRH power can only be treated by means of the bounce-averaged Fokker-Planck code [2]. The effect of the different magnetic configurations, however, is completely taken into account.

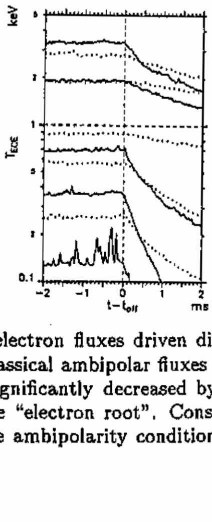

Fig. 2 *ECE electron temperatures after the ECRH is switched off for ECRH discharges (400 kW, X-mode at 140 GHz) with $n_e \simeq 1.5\ 10^{19}\ m^{-3}$ for configurations with slightly increased (solid lines) and nearly without ripple (neoclassically improved, dotted lines) at the ECRH launching: central, intermediate (from high field side) and outer channels (from low field side).*

The electron fluxes driven directly by the ECRH are shown in Fig. 3 in comparison with the neoclassical ambipolar fluxes for the discharge parameters of Fig. 1. These ECRH driven fluxes are significantly decreased by E_r, but less than the neoclassical ones at the transition region to the "electron root". Consequently, these "convective" electron fluxes dominate at high E_r in the ambipolarity condition. Within the traditional neoclassical transport theory (which is the basis for the DKES code [4] used at W7-AS), this discrepancy cannot be resolved since all fluxes are decreased with increasing E_r (e.g., the electron transport coefficients in the $\sqrt{\nu}$ regime scale with $E_r^{-3/2}$ which is the case in the "electron root" region). Due to the higher absorption for the X-mode scenarios, the $D_{\perp\perp}(v_\parallel, v_\perp)$ has a maximum closer to the thermal bulk than for the O-mode case. In case of X-mode, however, the power is mainly absorbed by deeply trapped electrons whereas in the O-mode case mainly by barely trapped electrons. In addition to the $v_{\nabla B}$ drift being proportional to energy, the energy dependence of the collisional detrapping leads to the broadening of the electron fluxes in the O-mode case. These results are well in agreement with the findings from the "effective power deposition" profiles by the electron heat wave propagation analysis [2].

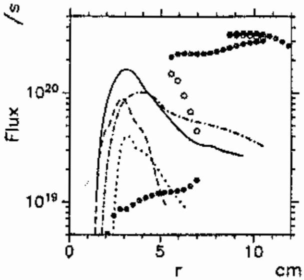

Fig. 3 ECRH driven fluxes from Monte Carlo simulation for $n_e \simeq 2\ 10^{19}$ m^{-3}, $T_e \simeq 3.5$ keV, and 400 kW heating power in the W7-AS "standard" configuration: with $E_r = 0$ (X-mode: solid, and O-mode: dot-dashed line), and with E_r corresponding to Fig. 1 (X-mode: dashed, and O-mode: dotted line). The ambipolar neoclassical fluxes (purely thermal) are given for reference (open circles: unstable root).

Effects of strong poloidal rotation: 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 $\underline{\nabla} \cdot \underline{v}_{\mathrm{E\times B}} \simeq -2\underline{v}_{\mathrm{E\times B}} \cdot \underline{\nabla} ln\, B$ drives a parallel flow (which is the equivalent to the Pfirsch-Schlüter current) as well as a (1*st* order) density inhomogeneity, n_1. In the ion force balance equation, the $(\underline{v} \cdot \underline{\nabla})\, \underline{v}$ term is approximately given by the gradient of the kinetic energy related to the poloidal rotation as well as the parallel flow. Viscous damping of this parallel flow by, e.g., ripple trapped particles leads to an enhanced density disturbance n_1 which, in turn, has to be compensated by a (1*st* order) potential, Φ_1, in the electron force balance equation. These effects can play an essential role mainly in the poloidal component of the force balance, and an external energy flux seems to be necessary to drive a strong poloidal rotation, i.e., the "electron root" feature.

On the other hand, the strong E_r leads also to modifications in the neoclassical transport. In the "usual" ordering, the $E \times B$ drift is assumed to be constant on flux surfaces (and terms of the order of $(\underline{B} \times \underline{\nabla} B) \cdot \underline{E}_r$ are neglected to allow for a mono-energetic solution). The only mode coupling in the Fourier expansion of the drift-kinetic equations appears due to the mirror term, $\underline{B} \cdot \underline{\nabla} B\, \partial f_1 / \partial p$ (with f_1 the 1*st* order distribution function, and $p = v_\parallel / v$), leading to all the neoclassical transport in the *lmfp* regimes. In addition to the $\underline{B} \cdot \underline{\nabla} \Phi_1\, \partial f_1 / \partial p$ in the self-consistent approach [5], also the $\underline{v}_{\mathrm{E\times B}} \cdot \underline{\nabla} f_1$ term leads to mode coupling, and, as a consequence, to a 1*st* order density and potential, n_1 and Φ_1, respectively. As this $\underline{v}_{\mathrm{E\times B}}$ is partly counteracted by the $v_\parallel$ term, this effect will be dominant in the ion drift-kinetic equation, whereas the 1*st* order potential affects both equations. Although no particle fluxes are driven by the Φ_1 with respect to (the 0*th* order) f_0, the energy flux is directly affected. With respect to f_1 (which leads to the usual neoclassical transport), the strong E_r will modify the particle and energy transport both for electron and ions in this self-consistent approach.

The bifurcation in the radial electric field: After flux-surface averaging of the poloidal component of the combined electron and ion force balance equation, the contributions of the pressure as well as of the kinetic energy (from rotation and parallel return flow) vanish. In this context, only the neoclassical predition of an "ion/electron root" transition based on the local ambipolarity condition is analyzed. With the shear viscosity in the divergence of the pressure tensor taken into account, the transition between both roots is smoothed out leading to a local violation of the neoclassical ambipolarity condition, i.e., to a radial current, $e(Z_i\Gamma_i - \Gamma_e)$, of different sign on both sides of the poloidal rotation shear layer. With the $\partial v/\partial t$ term from ion inertia, the (time dependent) diffusion equation equivalent to Ref. [1] is obtained (for simplicity, $\partial\hat{\eta}/\partial E_r = 0$ is assumed here for the normalized shear viscosity coefficient $\hat{\eta}$)

$$\frac{n m_i}{B^2}\frac{\partial}{\partial t}E_r = \frac{2}{r^2}\frac{\partial}{\partial r}r^2\hat{\eta}\left(\frac{\partial E_r}{\partial r} - \frac{E_r}{r}\right) - e(Z_i\Gamma_i - \Gamma_e).$$

Under the assumption of a stationary E_r, this diffusion equation leads for small $\hat{\eta}$ to the shear layer position, r_{SL}, within the region of several roots, see the solid line in the E_r plot in Fig. 1. With the current density, $e(\Gamma_i - \Gamma_e)$, roughly of the form $\propto (E_r - E_r{}^i)(E_r - E_r{}^{un})(E_r - E_r{}^e)$ where the index refers to the "electron", an unstable, and the "ion root", the diffusion eq. for E_r leads to a "bifurcation" problem which is quite similar to 1*st* order phase transitions in non-linear thermodynamics, e.g., see Refs. [6,7]. Within the poloidal rotation shear layer, the rotation energy is dissipated by viscosity leading to a damping mechanism adding to the one discussed in the previous section. Here, however, only the radial motion of r_{SL} can be analyzed (i.e., the flux-surface averaged force balance has one degree of freedom).

For the special scenarios with $T_i \ll T_e$ and the pronounced *lmfp* transport in W7-AS at the inner radii (here, the "effective" helical ripple is mainly determined by the toroidal mirror terms) the region with multiple roots of the ambipolarity condition is radially restricted. The thermodynamic arguments can only be applied in this region for estimating r_{SL}, i.e., in this picture the viscous damping of the poloidal rotation within the shear layer cannot be the main reason for the total disappearence of the "electron root". Then, in both the transition and the "electron root" region, the crucial point is related to the "current dependence" on E_r within the "electron root" region, i.e., the neoclassical $Z_i\Gamma_i(E_r) - \Gamma_e(E_r)$ dependence.

Conclusions: The "electron root" feature found at W7-AS with strongly positive radial electric fields is driven by the ripple-trapped suprathermal electrons generated by the ECRH. After switching-off the heating, the "electron root" feature disappears nearly immediately, i.e., on the same time scale as this ECRH driven flux. Monte Carlo simulations in 5D phase space clearly indicate that the additional "convective" electron fluxes are roughly of the same order of the ambipolar neoclassical prediction for the "ion root" at much lower E_r. For the predicted "electron root" E_r, the ambipolar fluxes predicted by the traditional neoclassical ordering are much too small. These findings indicate strongly, that the traditional neoclassical theory (at least for the ions) has to be checked in case of very strong radial electric fields.

Due to the variation of the magnetic field strength, a strong poloidal plasma rotation drives also a Pfirsch-Schlüter-like parallel flow on the flux surfaces, and, as a consequence, density and potential variations. This parallel flow velocities can give a significant contribution to the inertia term in the ion force balance. Although experimental indications of instabilities affecting the central confinement properties are missing so far, the "free energy" related to the strong poloidal plasma rotation as well as the parallel return flow may also be responsible for an "electrostatic" instability which superposes the neoclassical transport in the central region. All these features of the "electron root" at W7-AS, however, cannot be extrapolated to the high density scenarios with $T_e \simeq T_i$ in next generation stellarators. One essential aspect is the questionable reliability of the traditional neoclassical transport predictions for very strong radial electric fields as obtained in the "electron root" scenarios.

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