Optimum Confinement at W7-AS

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Introduction

During the few last experimental campaignes at W7-AS (modular stellarator with five toroidal field periods, pentagon-shaped magnetic axis, following the concept of reduced collisional transport by reducing the averaged toroidal curvature in a low shear configuration; $R = 2$ m, $a \leq 0.18$ m, $B_0 \leq 3$ T), regimes with an improved confinement were obtained. In particular, for pure NBI (neutral beam injection), $P_{\rm NBI} \leq 2.1$ MW, and for combined NBI + ECRH (electron cyclotron resonance heating) discharges, $P_{\rm NBI} \leq 1.35$ MW and $P_{\rm ECRH} \leq 800$ kW, "optimum" confinement properties (discharges with narrow density, broad temperature profiles and strongly sheared radial electric field close to the plasma edge) have been found, where the energy confinement time ($\tau_E \approx 50$ ms) exceeds the ISS95 scaling by at least a factor of two [1, 3, 4]. In these "optimum" confinement discharges, the particle fluxes as well as the energy fluxes (estimated from the particle and energy balances) are well in agreement with the neoclassical predictions up to 70% of the plasma radius. Fairly large negative E_r are measured at outer radii, with very strong shear of the $E \times B$ poloidal plasma rotation, being also consistent with the neoclassical predictions. Near the plasma edge the confinement is defined by fluctuations (as hypothesis), i.e. by the "anomalous" transport, and both the magnetic shear $\iota^{'}$ and the poloidal rotation shear, $E_r^{'}$, are expected to decrease the radial correlation length of the fluctuations [4], and, as consequence, to reduce the "anomalous" transport.

In high power ECRH discharges, with $P_{\rm ECRH} \leq 1.2$ MW at $B \simeq 2.5$ T (2nd harmonic X-mode, 140 GHz, launched from the low-field side), the predicted neoclassical "electron root" feature with highly peaked central electron temperatures ($T_e(0)$ up to 6 keV) has been observed [2, 3, 5]. In this central region, the reduction of the radial transport is related to a transition from the $1/\nu$-regime to the $\sqrt{\nu}$-regime due to an appearance there of strongly positive radial electric field, which is driven by the ripple-trapped suprathermal electron population generated by ECRH. There was found also the threshold combination of parameters [5, 6], required for establishing of the "electron root" feature, which depends on the magnetic configuration. In particular, whereas for the "standard" configuration with the mirror depth on axis of $\Delta B/B \simeq 5.5\%$ centrally peaked T_e profiles are measured except for the lowest ECRH power, this feature is only found at the highest ECRH power in the "low-mirror" configuration with $\Delta B/B \simeq 1.2\%$.

The analysis of these different confinement regimes is very important in order to have any preferences and expectations for the next device of this line - W7-X.

ECRH driven "electron root"

Two factors are definitive for the neoclassical transport at stellarators in the long-mean-free-path (*lmfp*) regime, radial ∇B-drift of locally trapped particles, and the poloidal $E \times B$ rotation of plasma. The ∇B-drift is responsible for an existence of the $1/\nu$-regime and leads in the collisionless limit to the nonlocal "convective" transport, i.e. direct loss-cone effects. The $E \times B$ rotation reduces the radial excursions of particles, and for strong values of E_r changes the electron transport from the $1/\nu$-regime, where $\Omega_E \ll \nu_{eff}$, to the $\sqrt{\nu}$-regime with $\Omega_E \sim \nu_{eff}$ ($\Omega_E = E_r/rB_0$ is the $E \times B$ poloidal precession frequency). Electron radial flux then is reduced, because the scale of radial excursion of electrons is defined by only the combination of both ∇B and $E \times B$ drifts (compare: in the $1/\nu$-regime only collisions limit the length of ∇B-drift, $\Delta r \simeq v_{dr}/\nu_{eff}$, making particles to be passing).

The local values of the radial electric field are determined by the ambipolarity condition, $\Gamma_e^{nc} = Z_i \Gamma_i^{nc}$, where $\Gamma_{e,i}^{nc}$ are the neoclassical particle fluxes. The stellarator transport coefficients depend on E_r themselves, and, as consequence, multiple roots (odd number) of the ambipolarity condition can appear. This feature exists only in the very *lmfp* regime.

In the case where T_i is not so far from T_e and $T_i^{'} \neq 0$, the "ion root" with slightly negative E_r is found in the inner region typically with flat or even hollow density profiles. The ion transport coefficients are strongly reduced by much smaller $|E_r|$ than the electron ones. At outer radii, i.e. in the region of the strong density gradients, the "ion root" can become strongly negative and is roughly given by $\Gamma_i^{nc} \simeq 0$. Note, that this root is equivalent to the unique solution of the ambipolarity condition if the transport coefficients do not content any dependence on E_r (like in tokamak configuration). This regime is rather usual for different scenarios at many devices.

For the special conditions of highly peaked T_e and fairly flat T_i profiles with $T_e \gg T_i$, a strongly positive E_r, "electron root", is needed to reduce Γ_e^{nc}. Strictly speaking, strong E_r reduces both electron and ion transport coefficients, i.e. significantly improves confinement.

In the experiments at W7-AS with high power ECRH scenario ($P_{\rm ECRH} \leq 1.2$ MW) the "electron root" regime of confinement was found for both "standard" and "low-mirror" configurations [2, 3, 5]. Because of more pronounced "electron root" feature for the "standard" configuration, all experimental results represented below are refered only to this case.

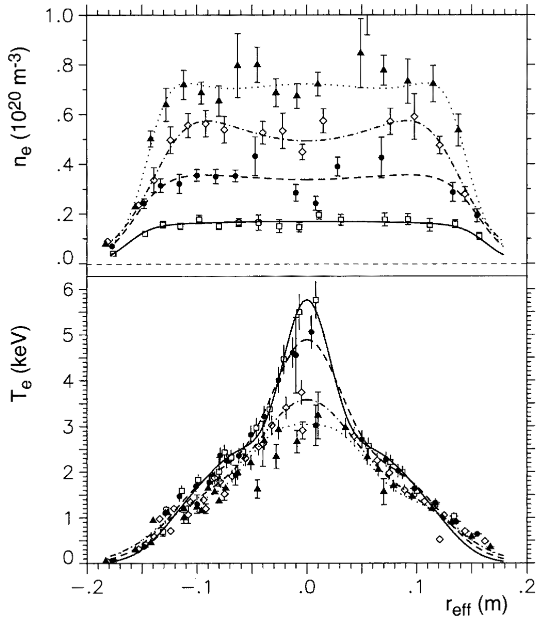

Figure 1: Density scan of the high power ECRH discharge ($P_{\rm ECRH} = 1.2$ MW at 140 GHz 2nd harmonic X-mode, low-field-side launching) for the "standard" configuration.

The results of the density scan for the power $P_{\rm ECRH} = 1.2$ MW (much more then the power threshold, i.e. > 400 kW), are presented on the Fig.1. The additional peaking of the central T_e profile is found for all densities, while outside of the "electron root" region the T_e profiles vary little in the density scan. Since the electron-ion collisional power transfer as well as radiative losses are fairly small, the $1/\nu$ dependence of the neoclassical transport coefficients, i.e. the electron heat flux being independent of density, is directly confirmed at these intermediate radii. For the strongly positive electric field of the "electron root" region, the thermal electron transport coefficients are mainly defined by the $\sqrt{\nu}$-regime scaling, and the expected fairly strong density dependence is in agreement with the density dependence of the highly peaked T_e profile.

The interpretation of these results as an appearance of the "electron root" is confirmed by the agreement between the experimental $E_r(r)$ profile and the neoclassical simulations (Fig.2, upper plot). Experimental values of E_r derived from the poloidal rotation measurements by active charge exchange recombination spectroscopy (CXRS). Strongly positive E_r has been obtained in the region with the peaked T_e profile, while at outer radii both the experimental and the predicted E_r are rather small ("ion root"). The electron heat diffusivity, χ_e, obtained from the power balance (Fig.2, lower plot), has a rather qualitative agreement with the predicted neoclassical values, and being much less than the reference values with $E_r = 0$. This agreement is reasonable up to $r \simeq 12$ cm (region $r > 12$ cm is the plasma periphery, where the "anomalous" transport dominates).

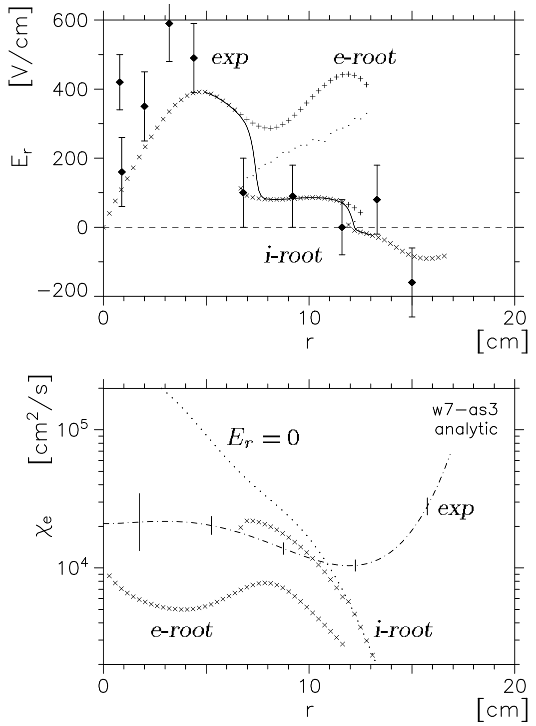

Figure 2: Radial electric field, E_r (upper plot), and electron thermal conductivity, χ_e (lower plot), vs radius, predicted (full curve and crosses) and measured (full diamonds), for $n_e = 2.0 \times 10^{19} m^{-3}$, $P_{\rm ECRH} = 800$ kW.

At W7-AS the ECRH launching system is located very close to the elliptical plane with a local minimum of $|B|$, where a significant fraction of ripple-trapped particles exists. Due to a small width of the wave beam (≤ 5 cm) and a large optical thickness of the plasma, the deposition profile is highly peaked as predicted by ray-tracing simulations showing an absorbtion up to 90% of the launched power within the effective radius of about 2 cm. Because of the highly localized deposition profile and existing there a significant fraction of locally trapped particles, the launched power is absorbed mainly by trapped electrons leading to a strong deviation of their distribution from the Maxwellian. Appearance of the nonthermal convective flux disturbes the ambipolarity ($E_r \lesssim 0$), and, as response, creates the positive E_r. If this disturbance is big enough, ion flux, being much more sensitive for any changes of E_r (and limited for response), cannot balance the increased electron flux, and the transition of electron transport from the $1/\nu$-regime to the $\sqrt{\nu}$-regime happens, suppressing the electron radial flux to ions level and establishing the conventional value of E_r. As consequence, the radial thermal flux ($Q_e \simeq -n_e\chi_e T_e^{'}$) degrades and improves the temperature dependences from an unfavourable $Q_e^{1/\nu} \propto T_e^{9/2}$ to $Q_e^{\sqrt{\nu}} \propto n_e^{3/2} T_e^{9/4}$.

With the hypothesis of the dominant role of the non-local (convective) radial flux of ripple-trapped suprathermal electrons, it should be possible to identify two time scales. The radial ∇B-drift time scale for the ripple-trapped electrons (especially for suprathermal ones) is much shorter than the energy confinement time. Without the ECRH-driven convective flux, the E_r in the "electron root" region would drop on the fast time scale (limited only by ion inertia), and nearly instantaneously the neoclassical fluxes should increase to the "ion root" level. Consequently, the highly peaked "electron root" T_e should drop much faster than the "ion root" T_e after the ECRH power is switched off or decreased under the power threshold. These different time scales can be identified from the ECE electron temperature traces.

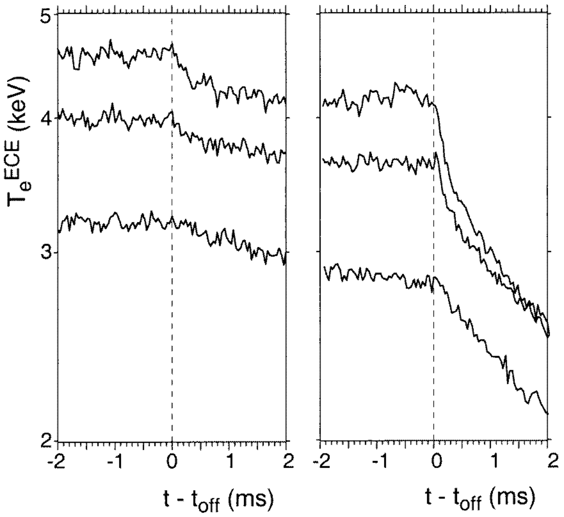

Figure 3: Time traces of T_e for central ECE channels, ($n_e \simeq 3.5\times10^{19} m^{-3}$). Left - $P_{\rm ECRH}$ switched from 1200 kW to 800 kW, and right - switched off from 800 kW.

The example in Fig.3 shows the dependence of the "electron root" feature on the ECRH power. After one (from three) gyrotron is switched off and $P_{\rm ECRH}$ reduced from 1.2 MW to 800 kW (left plot), the electron temperatures are only slightly decreased, and no fast transition is found. The central T_e profile remains highly peaked. After other gyrotrons are switched off (right plot), the central peaking of the T_e profile and the "electron root" feature disappears within 0.3 ms which is much faster than the thermal decay after this transition.

The good agreement between the experimental data and the neoclassical predictions (DKES simulations) seems to be a little artificial, because of the *nonthermal* origin of the observed "electron root" feature. In fact, the ECRH driven distortion from the Maxwellian produces the additional convective flux, $\Gamma_e^{\rm ECRH}$, which being included into the ambipolarity condition plays an essential role, while the neoclassical simulations are based on the assumption of slight deviation from the thermal equilibrium, driven only by the gradients of $T_{e,i}$ and n_e (i.e. by the thermodynamic forces). Moreover, in experiments at $B = 1.25$ T with reduced ECRH heating power at 70 GHz with $P_{\rm ECRH} \leq 250$ kW [3], no "electron root" were observed, neither by CXRS (only $E_r \lesssim 0$ measured) nor by the experimental χ_e analysis, while DKES simulations clearly predicted the "electron root" establishing within the heated central region. These results remain many opened questions and need more detail and careful investigations.

"Optimum" confinement discharges

Despite of the significantly improved transport properties, pure ECRH "electron root" scenarios have no perspectives for a fusion plasma, because of really slight coupling of ions and electrons ($T_i \ll T_e$). From this point of view, NBI scenarios as well as a combination of both NBI and ECRH, are the more attractive, leading to an effective heating of both electrons and ions with $T_i \approx T_e$.

In high power pure NBI and combined NBI + ECRH discharges, narrow density profiles in combination with broad temperature profiles have been observed (Fig.4, full and dot-dashed curves). Fairly steep T_e gradients are measured (Ruby and YAG Thomson scattering, ECE), especially in the outer region of low densities ($r \approx$ 12-15 cm). For this type of discharges, performed at a rotational transform of $\iota \simeq 1/3$ and shifted by a vertical field onto the inboard limiters, "optimum" confinement properties are found with $T_e \gtrsim T_i$ up to 1.5 keV, and the energy confinement time $\tau_E \approx 50$ ms, exceeding the ISS95 scaling by at least a factor of two.

Good wall conditioning and very low recycling are strongly required in order to obtain the narrow density profiles and to provide the global density control even for high NBI power levels (with a particle source strength of up to $2.5 \times 10^{20} s^{-1}$) [1]. Low recycling is obtained by boronization and He glow-discharge conditioning. For NBI heated discharges under unfavourable recycling conditions, however, much broader density profiles and significantly lower temperatures were found (see Fig.4, dashed curve). These quite different profiles have been obtained with different plasma limitation scenarios: (1) by symmetrically placed inboard limiters, and (2) by movable limiters placed on the top and bottom in the significantly elongated (elliptical) planes. These two cases provide quite different recycling conditions. At the elliptical plane the flux surface radial expansion is large so that the recycling sources for the top and the bottom limiters are located at the

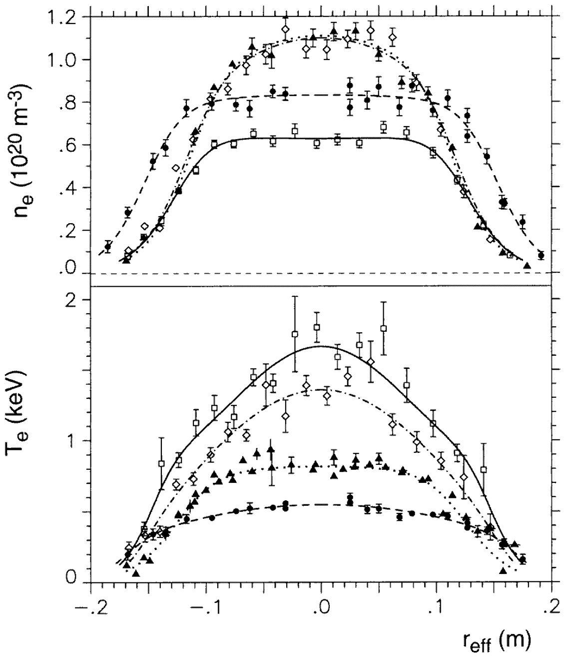

Figure 4: Electron density and temperature profiles for "optimum" confinement conditions with pure NBI and combined NBI + ECRH (full curve: combined scenario, P_{NBI} = 1.35 MW and P_{ECRH} = 750 kW; dot-dashed curve: combined scenario, P_{NBI} = 1.30 MW and P_{ECRH} = 350 kW; dotted curve: pure NBI (450 kW). As referense is shown the discharge with "degraded" confinement (dashed curve) for pure NBI (850 kW).

very outside of the plasma. For the inboard limiters, however, the flux expansion is much smaller, and, consequently, neutrals can penetrate much deeper into the plasma, thus leading to the narrow density profiles.

Fig.5 shows the experimental data and the results of analysis for the combined NBI (830 kW: 320 kW to electrons and 510 kW to ions) and ECRH (350 kW, 2nd harmonic X-mode, 140 GHz) [3]. Again, a vertical magnetic field is applied for a close inner limiter contact. For this type of discharges the radial ion transport dominates, thus only the negative E_r ("ion root") is expected. The predicted E_r obtained from the ambipolarity condition is well consistent with the experimental finding even at the outer radii, where the ambipolar neoclassical fluxes become very small.

The particle balance analysis indicates that the particle diffusivity at outer radii increases significantly with decreasing density. Then, for the narrow profiles with very low edge densities, the outer flux (being limited by particle sources at inner radii) determines the shape of the outer n_e profile. For the broad density profile, in contrast, the flux increases with radius (the outer particle sources decay strongly with the distance from the limiter). Thus, the density profile roughly reflects the outer particle sources which, in turn, depends on the density profile. The particle fluxes at the plasma edge (DEGAS and EIRENE simulations) are higher by a factor of about two and decay much faster with distance from the limiter in the case of the broad density profile compared to the narrow ones (Fig.5, right plot). Moreover, the outer (narrow) density profile is - within experimental errors - independent of both the central density and the heating power. This result (see Fig.4) supports the simple picture, that the shape of the density profile depends mainly on the recycling conditions, determined by limiter position and material composition. However, since the "optimum" confinement regime with narrow density profile establishes under NBI heating conditions, central fueling (by NBI) also contributes to the density profile peaking.

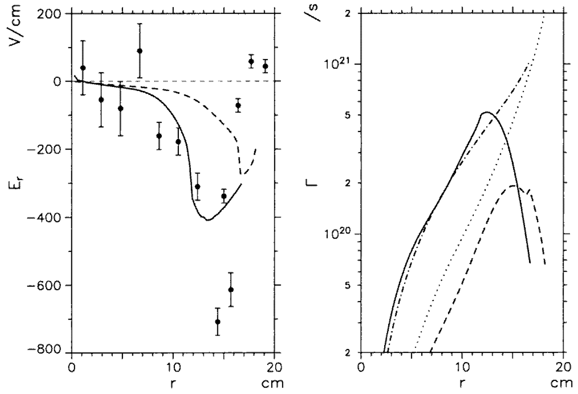

Figure 5: Left: radial electric field profile, measured (full dots) and predicted (full curve); dashed curve shows the predictions for "degraded" confinement discharge. Right: experimental particle fluxes, derived from EIRENE code (dot-dashed curve), and neoclassical predictions from DKES code (full curve) for "optimum" confinement discharge. As reference, the "degraded" confinement discharge shown: experiment (dotted) and prediction (dashed curve).

For effective radii $r \gtrsim 13$ cm recycling particles play a crucial role for the heat fluxes. These sources increase the local particle fluxes (see Fig.5, right plot) by an anomalous contribution, strongly dominating over the neoclassical ones. As a consequence, the global energy confinement is determined by the turbulent edge transport. According to the reflectometry, the level of turbulence in the region of the steep temperature gradients is considerably reduced for these discharges in comparison to purely NBI or ECRH heated ones with comparable plasma parameters. It is therefore speculated that the reduced electron density fluctuations as a result of the $E \times B$ flow shear result in reduced energy fluxes in the gradient region, thus presumably provoking the concomitant improvement in the global energy confinement.

In order to separate the effect of the narrow density profile and the formation of the steep temperature gradients close to the plasma edge, an "H-mode" discharge under clear separatrix conditions (at $\iota \simeq 1/2$) and with pure NBI heating was established. After the density-ramping phase (by applying a sufficient gas pulse), a "quiescent H-mode" phase with a broad density profile, but fairly low

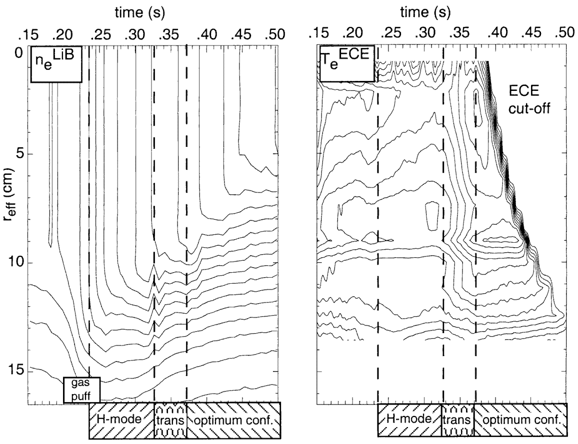

Figure 6: Contour plots of density (left, from Li-beam diagnostic), and electron temperature (right, from ECE) against radius and time. The "quiescent H-mode", the transition and the "optimum" confinement phases are indicated.

temperatures developed (see Fig.6). For this case, the neoclassical prediction for the energy fluxes is too low compared with the power balance. In a further transition (between 0.32 s and 0.36 s), the density profile narrows and the regime of "optimum" confinement with narrow density profiles, as described previously, develops with the identical features of the NBI discharges with contact to the inboard limiters at $r \simeq 0.34$ (see Fig.4, dotted curve). A sequence of spontaneously evolving huge edge localized modes (ELMs) may lead to a strong particle pump out at the edge and allow for the transition to the state with the narrow density profile. This ELM activity in the transition phase is located very close to the separatrix (only found in the outer interferometry channel). Within this transition phase, despite energy losses associated with the ELMs, a broad temperature profile with steep gradients at the outer radii establishes within about 20 ms which is comparable to the energy confinement time. After the strong ELM activity has disappeared, the central density continues to increase (loss of the density control with NBI fueling leads to the cut-off in the ECE measurements of T_e), but also the profile further narrows. In this "optimum" phase, the bulk energy transport is again in agreement with the neoclassical prediction.

Summary

Experimental transport analysis of the "optimum confinement" discharges at W7-AS for both types of high power scenarios discussed above, "electron root" scenario (pure ECRH) and "ion root" scenario (pure NBI and combined NBI + ECRH), have well confirmed its consistence with the neoclassical theory, if the bulk plasma has sufficiently high temperatures. This conclusion holds for the ion and electron heat conduction as well as for the particle transport.

For high power ECRH discharges highly peaked electron temperature profiles have been observed, which are identified as the "electron root" feature with an essentially improved energy confinement. The neoclassical electron *lmfp* transport is strongly reduced by the positive radial electric field, which is driven by the convective suprathermal electron flux. With the transition from the $1/\nu$- to the $\sqrt{\nu}$-regime the energy fluxes change the temperature dependence from the unfavourable $Q_e \propto T_e^{9/2}$ to the improved $Q_e \propto T_e^{9/4}$, leading to a significant improvement of the energy confinement in the plasma center (peaked T_e profiles with $T_e(0)$ up to 6 keV).

Existence of the suprathermal ripple-trapped population of electrons is an mandatory to observe the transition into the "electron root" regime. This circumstance being found experimentally is not included into the used neoclassical models, because of very nontrivial character of this work, and the analysis requests to be very careful in any conclusions, dispite of any agreement between the experiments and predictions.

Global confinement properties are strongly dependent on the broadness of the density profiles and the recycling conditions. Only for narrow density profiles do steep temperature gradients develop in the region of low densities leading to "optimum" energy confinement. Maximum energy confinement times ($\tau_E \approx 50$ ms, that exceeds the ISS95 scaling by factor two, at least) and maximum ion temperatures ($T_i \lesssim 1.5$ keV) are achieved for discharges with strongly negative radial electric field at the outer radii, preferably for the combined high power heating scenarios NBI + ECRH. Low wall recycling, resulting in low edge densities, is a prerequisite to obtain this scenario, otherwise the density control is lost. Experimental values of E_r and values of particle and energy fluxes are in a good agreement with the neoclassical predictions up to 70% of plasma radius. Strongly sheared E_r at outer radii may act like a transport barrier, affecting the observed fluctuation level and forming the narrow density profile and steep gradients of temperature.

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