

Optimized confinement discharges with high ion temperatures after installation of the island divertor in W7-AS

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1. Introduction to optimized confinement regime at W7-AS

Optimized confinement (OC) regime with an energy confinement time more than twice as large as predicted by the International Stellarator Scaling *ISS95* was already obtained at Wendelstein 7-AS in the limiter configuration [1, 2] before it was equipped with an island divertor. Power and particle balances in OC turned out to be neoclassical in the region within 2/3 of the minor plasma radius and anomalous in the outer third.

OC was accessed in the discharges, where the plasma was shifted to the inner wall by a vertical magnetic field. In this configuration the last closed flux surface was defined by the inboard limiters but not by the top/bottom limiters as in the standard configuration. Avoiding certain rotational transform ι values causing low confinement [3], it was possible to achieve the OC regime at $\iota \approx 1/3$ as well as at $\iota \approx 1/2$ ($B_0=2.5$ T). The combined NBI/ECR heating with up to three NBI sources of ≈ 400 kW nominal power each and one or two gyrotrons of ≈ 350 kW each was preferable to access high ion temperatures. The neutral beam injection provided a direct heating of ions and an effective central plasma fuelling. A further increase of the NBI heating power was restricted by an uncontrolled density rise.

The specific feature of OC was a narrow plasma density profile with low density at the edge. This type of density profile could only be accessed at low recycling rates and efficient plasma fuelling. Therefore the wall condition was crucial for OC. The inboard limiters with their large area allowed a more homogeneous edge plasma leading to a reduced recycling in comparison to the top/bottom limiter configuration. In addition, owing to the plasma elongation, the neutral particles recycled at the inboard limiters could penetrate deeper into the plasma than those from the top/bottom limiters. It results in a better fuelling efficiency and helps to sustain low density at the edge.

The ion and electron temperature profiles were relatively broad in OC with $T_e > T_i$ of up to 1.5 keV in the center (highest T_i in W7-AS so far) and $T_e \approx T_i$ in the outer part. Large gradients of T_e and T_i in the region of low density led to the formation of a strong negative radial

electric field E_r of up to -800 V/cm in the outer third of the plasma radius. The electric field reduced the neoclassical transport in the LMFP regime in the bulk plasma. The $E \times B$ shear reduced the anomalous transport at the plasma edge.

Recently, W7-AS was equipped with an island divertor [4] to investigate this concept of plasma exhaust similar to the one planned for W7-X. Considering the OC regime, there was some suspense concerning its compatibility with the divertor configuration. First of all, high recycling at high edge densities was expected to be the standard operational mode for the divertor, which might be fatal for the OC regime. Furthermore, the divertor module positioning is similar to that of the old top/bottom limiters, the configuration unfavourable for OC. Additionally, the plasma volume became smaller after the divertor installation. Hence the overall performance of OC was expected to become poorer.

In this paper we present the results of the experimental campaign carried out in order to reach high T_i in the OC regime in the divertor machine and to compare the outcome with the old inboard limiter configuration. The experiments were done at $\tau \approx 1/3$ as well as at $\tau \approx 1/2$ ($B_0 = 2.5$ T) in a hydrogen plasma. For the $\tau \approx 1/3$ configuration power balance calculations by the neoclassical transport code DKES [5] were performed to verify the experimental findings.

2. Experiments in OC in divertor machine and neoclassical calculations

Several experiments were recently carried out with the goal to achieve high ion temperatures. In some particular discharges at low densities T_{i0} reached 1.6 keV, the highest value in W7-AS so far. Here we present two well documented series of reproducible discharges at $\tau \approx 1/3$ and $\tau \approx 1/2$ and medium density ($n_{e0} \approx 7 \cdot 8 \cdot 10^{19} \text{ m}^{-3}$). T_i was measured actively by neutral particle analysis (NPA) and CXRS at H- and Li-beams, T_e by ECE and Thomson scattering of the ruby and YAG lasers, n_e by ruby, YAG and beam emission of Li-beam. The E_r profile was obtained from C^{6+} ion velocity measurements by CXRS with Li-beam [6].

Figure 1 shows the plasma profile measurements at $\tau_a = 0.355$. Here, the plasma was heated by

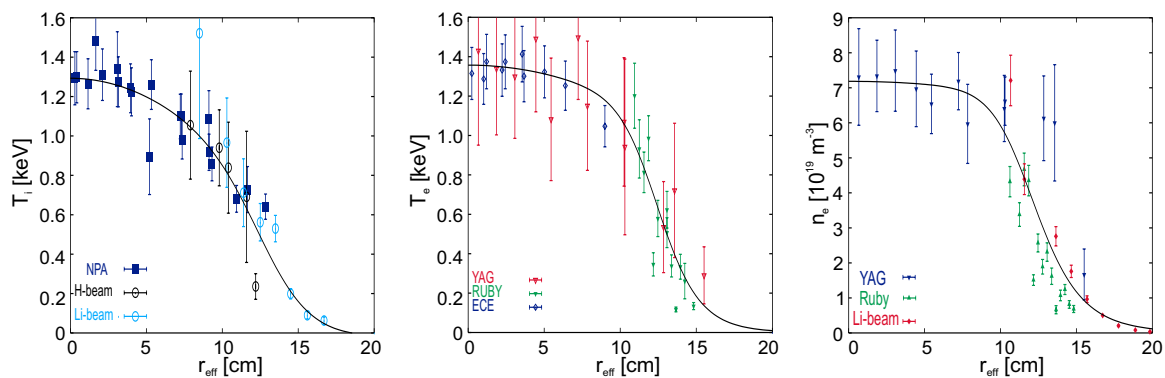


Figure 1. Profiles of T_i , T_e and n_e with fits used for calculations (#54285-54296, $\tau_a = 0.355$)

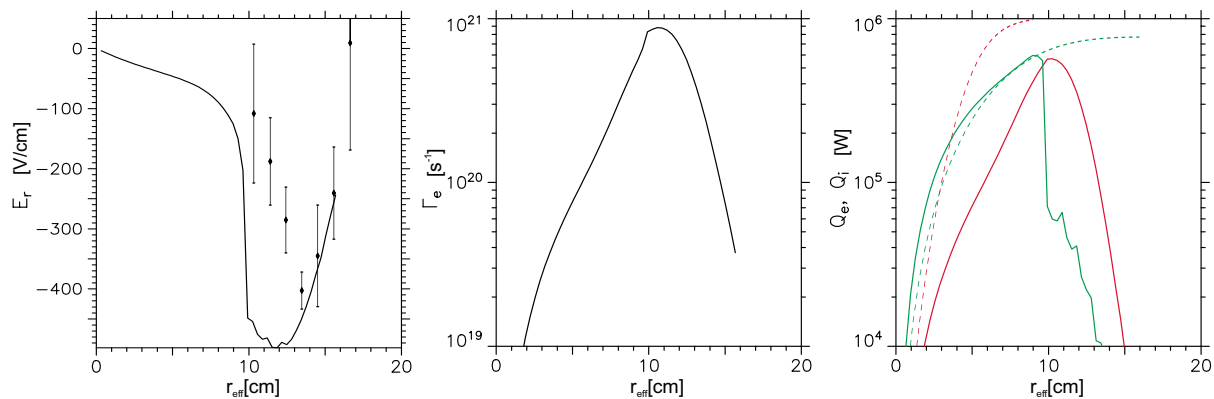


Figure 2. Neoclassical calculations by DKES: E_r (left) in comparison with the measured profile, Γ_e (middle) and Q_e (calculated – red full curve, estimated experimental – red broken) and Q_i (calculated – green full curve, estimated experimental – green broken) (right)

four NBI sources with a total deposited power of ≈ 1.3 MW and two 140 GHz gyrotrons with totally ≈ 0.9 MW. The energy content in these discharges was higher than 20 kJ. For the numerical analysis the profiles were fitted by analytical functions. The profile shapes are similar to those obtained in the limiter machine. Using these profiles, calculations by the neoclassical transport code DKES were done. The results for the radial electric field E_r (obtained from the ambipolar fluxes), electron flux Γ_e , heat fluxes by electrons Q_e and ions Q_i are shown in figure 2. There is a good agreement between measured and calculated E_r , which reaches a negative value of higher than -400 V in r_{eff} coordinates. In real geometry, depending on the position in the torus and the flux compression, negative E_r can be as high as -800 V.

At the moment of the paper submission the heating power deposition profiles for this discharge series were not available, so we only could roughly estimate the values of Q_e and Q_i in the experiment. The calculated Q_i agrees well with the experimental one in the bulk plasma up to 10 cm radially. This stresses the neoclassical nature of this regime. In the outer region there is a discrepancy between calculated and measured Q_i indicating anomalous transport there. In contrast, estimated experimental Q_e lies well above the calculated one for the whole

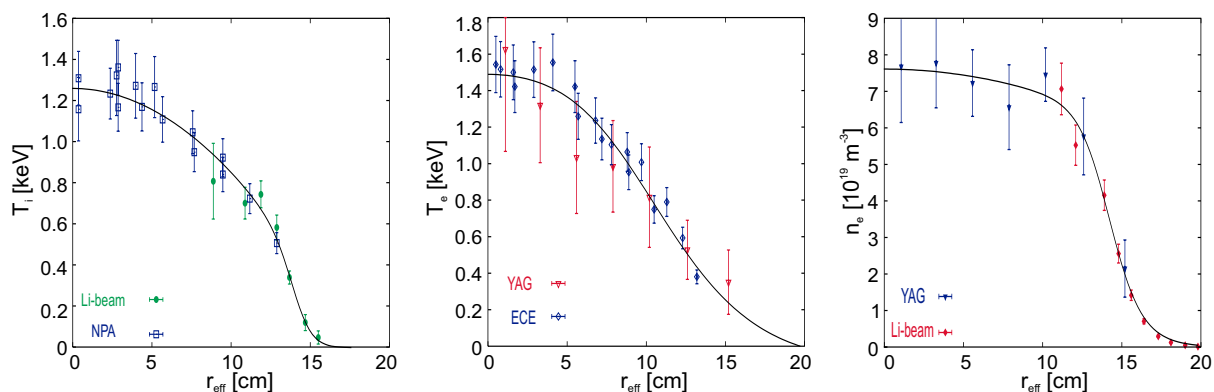


Figure 3. Profiles of T_p , T_e and n_e (#54233-54241, $\tau_a=0.515$)

radial region. It is not clear so far, if this discrepancy results from the incorrect estimation, or if it is an indication of the anomalous electron transport in the discharges with an extremely high electron heating. A further analysis is necessary to clarify this.

Figure 3 shows the plasma profiles in the series at $\tau_a=0.515$. Here, the heating scenario was the same as for the series at $\tau_a=0.355$ resulting in the same energy content of 20 kJ. As one can see, change of the magnetic field configuration does not perturb the quality of the OC regime. Also here high T_i are possible, up to 1.6 keV in some discharges. The impurity behaviour and pinch velocities obtained for this discharge series are presented in [6].

3. Summary and discussion

Contrary to some doubts listed in “Introduction”, the installation of the island divertor in W7-AS did not deteriorate the accessibility of OC. In the divertor machine, the recycling has been decreased leading to the robust OC regime. The confinement quality does not depend on the wall condition as much as in the inboard limiter configuration. The density control is now possible in discharges heated by up to 4 NBI sources. The highest central ion temperature of 1.6 keV was achieved despite the reduced effective minor radius. Deviations from the optimal discharge parameters and decrease of the heating power by about 1/3 resulted in a reduction of T_{i0} of 10-15 % only. Radiative power losses of less than 10 % of the heating power in OC indicate a low concentration of impurities. The large radial electric fields needed to reduce the neoclassical transport in the LMFP regime and thus to obtain OC are well established under divertor conditions. The achieved temperatures, however, are limited by the strong temperature dependence of the neoclassical transport properties. The comparison of the estimated experimental power balance with that calculated by the DKES code verifies the neoclassical nature of OC for ions. The discrepancy in the electron heat fluxes might indicate an enhanced transport owing to a high electron heating.

The next step for the investigation of OC would be experiments at higher densities in the divertor configuration with the island structure at the edge to study further the compatibility of OC with divertor, particularly with regard to the possibility of OC as an operational mode in W7-X.

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