Plasma profiles in 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 in W7-AS

Before Wendelstein 7-AS was equipped with an island divertor, the plasma boundary was defined by a number of limiters. In the standard configuration these were the top/bottom rail limiters. The “normal” confinement (comparable with L mode in a tokamak) in this configuration was characterized by high recycling rates, broad density profile and flat electron and ion temperature profiles. The ion temperature did not exceed 1 keV in this regime.

Optimized confinement (OC) regime [1,2] was accessed in the discharges with the plasma shifted towards the inner wall by a vertical magnetic field. In this case the plasma boundary was defined by the inboard limiters. The specific feature of OC was a narrow density profile with low density at the edge. This type of the 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 resulted in a better fuelling efficiency and helped to sustain low density at the edge.

An energy confinement time more than twice as large as predicted by the International Stellarator Scaling *ISS95* with a maximal value of 55 ms was obtained in OC discharges. 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.

The ion and electron temperature profiles in the limiter machine were relatively broad in OC with $T_e > T_i$ of up to 1.5 keV in the center 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 ExB shear reduced the anomalous transport at the plasma edge.

Avoiding certain rotational transform $\iota\!\!-$ 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. ECRH helped to sustain the plasma density by reduction of the particle confinement time. Moreover, ECRH increased T_e leading to a better heating efficiency of ions by NBI.

In the last two years of operation W7-AS was equipped with an island divertor [4] to investigate this concept of the 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, it was doubtful if low recycling needed for OC can be obtained in the divertor configuration. 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.
First experiments on OC after island divertor installation were done at medium plasma density in the configuration at $\iota \approx 1/3$ without islands and at $\iota \approx 1/2$ with reduced island width [5]. It was shown, that despite the concerns about the OC compatibility with divertor the performance of the OC regime became even more robust to changes in the magnetic field configurations and discharge heating scenarios.
In this paper we present the results of the further plasma profile evaluation in the discharges from [5]. Additionally, results of the experiment at a higher density in the divertor configuration at $\iota \approx 5/10$ are presented. Such a divertor configuration is important particularly with regard to W7-X. Calculations by the neoclassical transport code DKES [6] were carried out to verify the experimental findings.

2. Diagnostics for plasma profile measurements at W7-AS

W7-AS was equipped with a variety of diagnostics for the measurements of electron density, electron and ion temperature profiles and profiles of some other plasma properties. They allowed redundant as well as complementary determination of the profile shapes with a good spatial resolution, which is needed for the further transport analysis by numerical calculations. Unfortunately, not all of these systems were available for every experiment considered here.
For the measurements of the electron density profile three different systems were used. The Thomson scattering system based on a YAG laser delivered time-resolved profiles for the central and gradient regions with a moderate radial resolution. The other Thomson scattering diagnostic, which was based on a ruby laser, could produce one profile per shot alternatively for the central or for the gradient region with a high radial resolution. The third technique was beam emission spectroscopy at a Li beam, which gave the time-resolved profile information for the gradient region and plasma edge with a high radial resolution.
There were also three tools to measure the electron temperature profile. Besides both Thomson systems an ECE system was available in some shot series delivering time-resolved T_e values with a good radial resolution throughout the whole profile.
For the confinement mode with high ion temperatures the T_i diagnostics were of particular importance. Two of them, neutral particle analysis (NPA) and charge-exchange recombination spectroscopy (CXRS), were based on a high-energetic diagnostic hydrogen beam. The NPA system was equipped with four movable analysers capable of time-resolved T_i measurements. Depending on the required radial resolution a series of 5 to 9 reproducible discharges was necessary to obtain a T_i profile in the central and gradient regions. The H beam CXRS diagnostics delivered data also for the central and gradient regions with a moderate radial resolution. CXRS on the high-energetic Li beam could deliver ion temperature, poloidal rotation and carbon concentration in the gradient and edge regions with a high radial resolution averaged over time of the flat-top phases. Edge T_i from the passive BIV spectroscopy was used for the cases where the Li beam data were not available.
The radial electric field was calculated from the radial force balance using the pressure gradient and poloidal rotation both measured on the Li beam [7].
To increase the accuracy of the measurements, the data of every diagnostic were averaged, when possible, over all discharges in a series and their flat-top phases.
All those profile diagnostics were placed in different toroidal and poloidal positions around the torus. Transformation of the radial positions from real to effective radial coordinate is afflicted of some uncertainty. This influences also the profile fits, which are used for transport analyses. To transform the profiles used in this work the codes TRANS (calculates r_{eff} for

configurations with nested flux surfaces and ß values of up to 1 %) and NEMEC (can handle arbitrary ß values with influence of the plasma current for nested flux surfaces).

3. Experiments on OC in divertor machine and neoclassical calculations

In our first experiments on the OC regime in the machine equipped with the island divertor we started in a quite conservative manner: at a medium density (n_{e0}≈7-8·10^{19} m^{-3}) in the configurations at ι ≈1/3 without natural islands, where the divertor served as a limiter, and at ι ≈1/2 with reduced island width. Shortly before the shutdown of W7-AS a series in one of the standard divertor configurations with 5/10 island boundary was carried out.

The main parameters of the discharge series at ι ≈1/3 were as follows: central toroidal magnetic field B_0=-2.54 T (“-“ means the same direction as the neutral beam injection), vertical magnetic field B_v=-23 mT (plasma shift inwards) and edge rotational transform ι_a=0.355. The plasma was heated by four NBI sources with a total deposited power of ≈1.3 MW and two 140 GHz gyrotrons with totally ≈0.9 MW. Despite the high NBI power the density could be kept constant for the whole discharge flat-top phase. The energy content in these discharges was higher than 20 kJ, a quite high value for W7-AS. Figure 1 shows the profiles of this discharge. Compared to [5], a further stage of evaluation is presented here, corresponding the NEMEC transformation for ß=1.3 % and calculated plasma current profile.

For the numerical analysis the profiles were fitted by analytical functions. The profile shapes are similar to those obtained in the limiter machine [1]. Using these profiles, calculations by

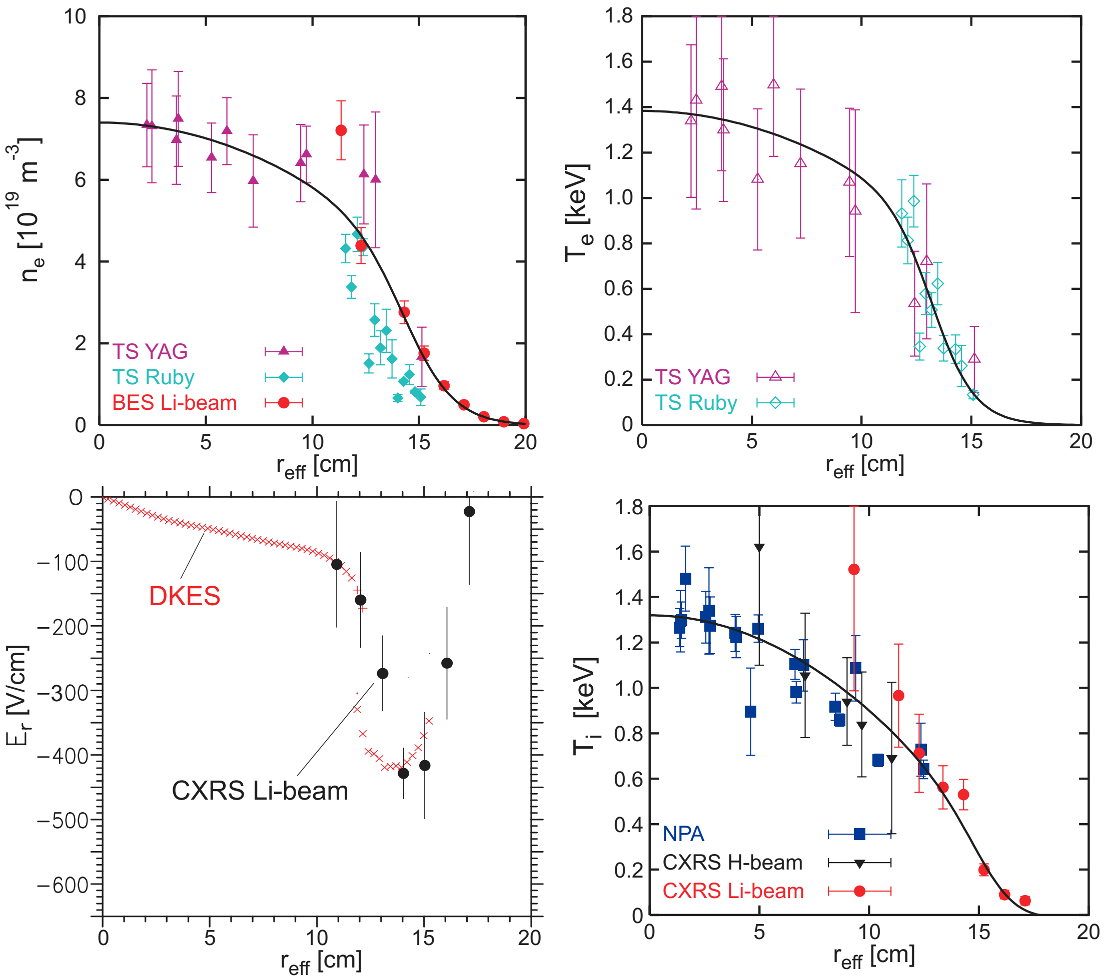

Figure 1. Profiles of n_e, T_e and T_i with fits used for calculations (#54285-54296, ι ≈1/3). E_r calculated by DKES and measured by Li beam is also shown.

the neoclassical transport code DKES were done. The results for the radial electric field E_r (obtained from the ambipolarity condition for electron and ion particle fluxes) are in excellent agreement with measured E_r, which reaches a negative value of higher than -400 V in r_{eff} coordinates. In real space, depending on the position in the torus and the flux compression, negative E_r can be as strong as -800 V.

Figure 2 shows the plasma profiles in the series at ɫ ≈1/2. The configuration properties of these discharges were: B_0=-2.51 T, B_v=-13 mT and ɫ$_a$=0.52. The natural island width was reduced by in-vessel control coils with a ratio to the modular coil current of I_{cc}/I_m=0.06. The heating scenario was the same as for the series at ɫ ≈1/3 resulting in the similar energy content of 20 kJ. Comparing both series one can see, that the change of the magnetic field configuration does not perturb the quality of the OC regime with high ion temperatures in the center of 1.3-1.4 keV. Large density and temperature gradients in region r_{eff}/a >2/3 lead to an even stronger radial electric field calculated by the DKES code and confirmed by CXRS measurements.

The discharge series in the divertor configuration at ɫ ≈5/10 was done at B_0=-2.51 T, B_v=-13 mT and ɫ$_a$=0.52. The island width was increased by a control coil current of I_{cc}/I_m=-0.057. The discharge was split up in three heating phases (figure 3) of pure ECRH, then ECRH plus two NBI sources and ECRH plus three NBI sources. To come nearer to the divertor operational regime the density was increased in comparison to the series above and was

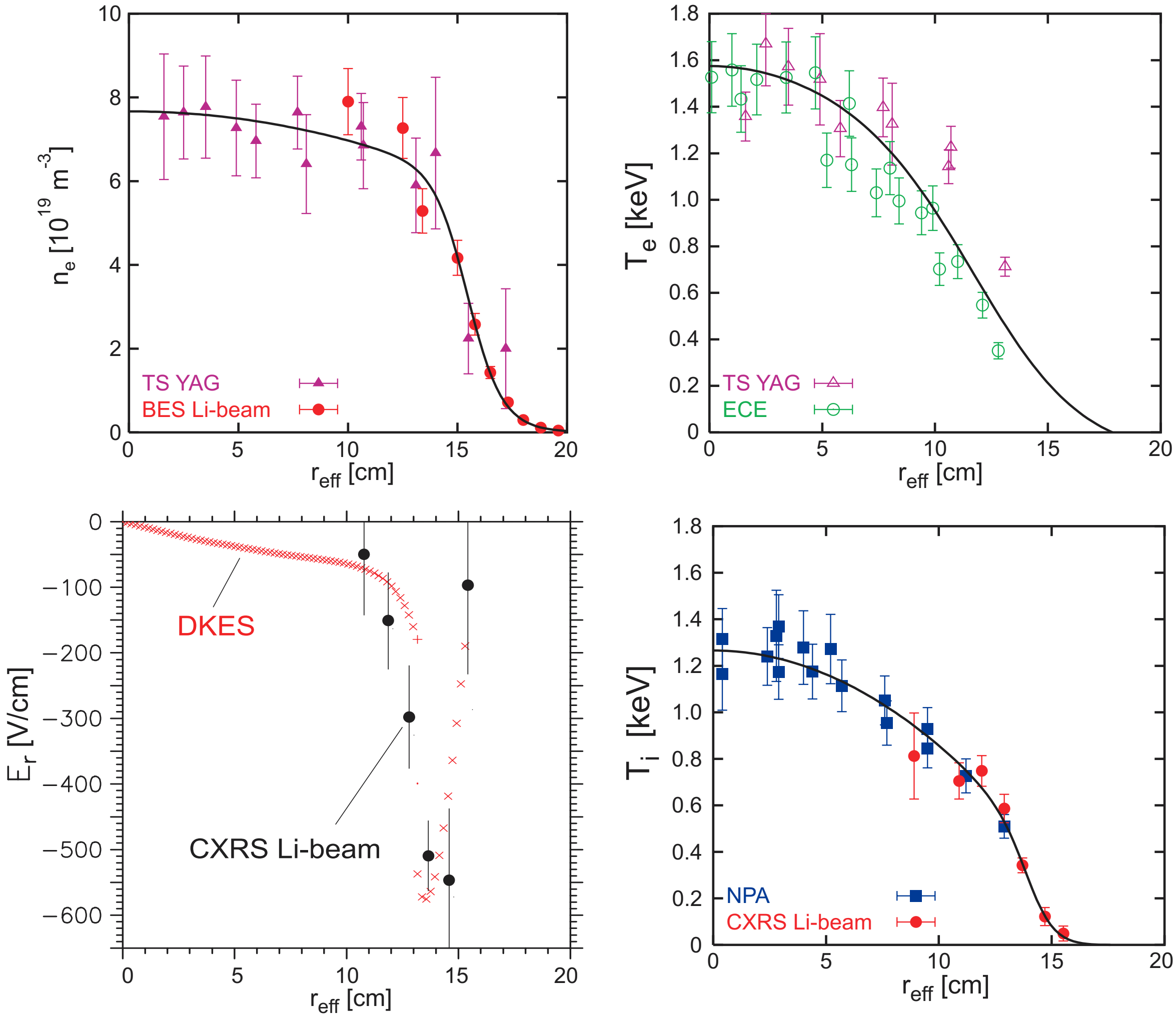

Figure 2. Profiles of n_e, T_e and T_i with fits used for calculations (#54233-54241, ɫ ≈1/2). E_r calculated by DKES and measured by Li beam is also shown.

chosen just below the ECRH cut-off density.
Interesting, that also during pure ECRH a good confinement regime with W_{dia} of slightly below 20 kJ was obtained. A large negative electric field calculated by the DKES code also confirms the OC regime in this phase. The plasma profiles for this case are shown in figure 4. The ion temperature reaches 0.9 keV in the centre in spite of absence of the direct auxiliary ion heating. This can be explained by the small equipartition time between electrons and ions at that relative high density.

4. Summary and discussion

Contrary to some concerns 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 is not sensitive on the wall condition as much as in the inboard limiter configuration. The plasma positioning does not play a crucial role as well. The density control is possible in discharges heated by up to 4 NBI sources.
There is a two-fold influence of the negative radial electric field in the OC regime. In region r_{eff}/a <2/3 with neoclassical transport it switches the LMFP transport regime from unfavourable $\sim 1/\upsilon$ to $\sim\sqrt{\upsilon}$ or ever tokamak-like $\sim\upsilon$ regime with correspondingly lower neoclassical transport properties. In region r_{eff}/a >2/3 dominated by anomalous transport the *ExB* shear reduces this turbulence-driven transport.
The highest central ion temperature of 1.7 keV was achieved in some particular OC discharges 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 10-20 % only. The achieved temperatures, however, are limited by the strong temperature dependence of the neoclassical transport properties. Radiative power losses of less than 10 % of the heating power in OC indicate a low concentration of heavy impurities. The carbon impurity concentration and transport for discharge series at $\iota \approx 1/2$ is investigated in [8].

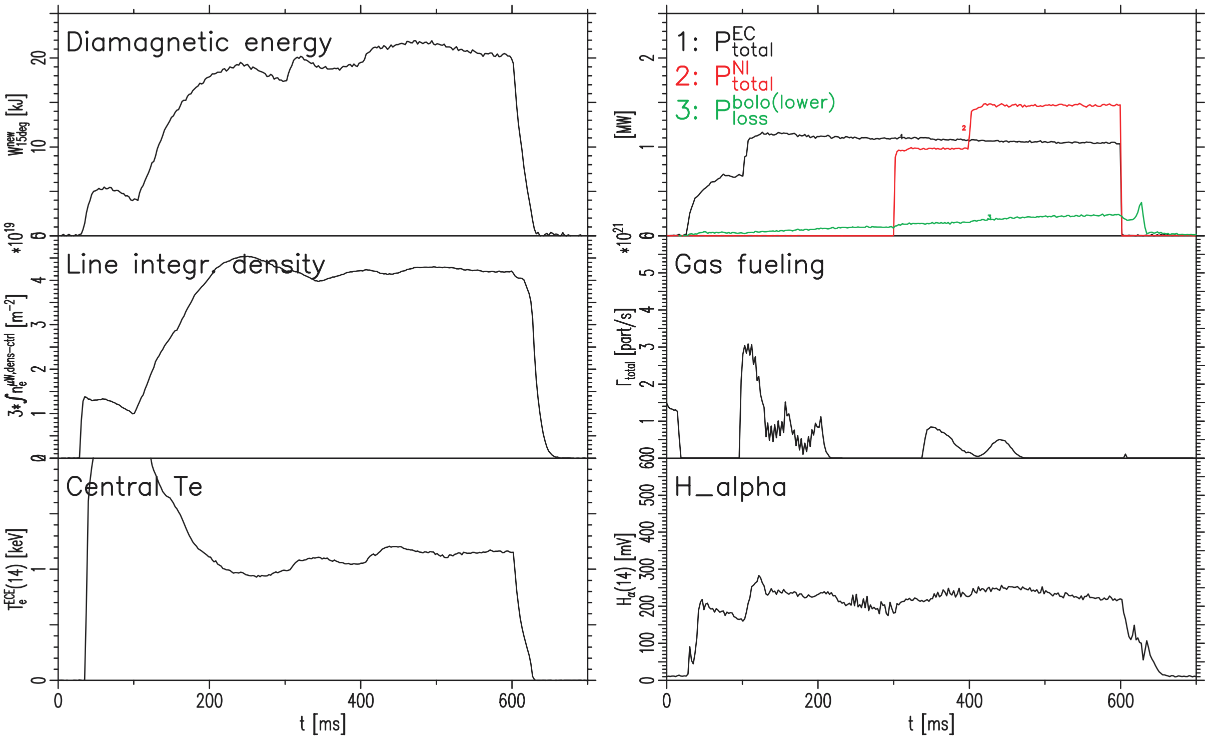

Figure 3. Time evolution of one of the discharges from series at $\iota \approx 5/10$ (#56688)

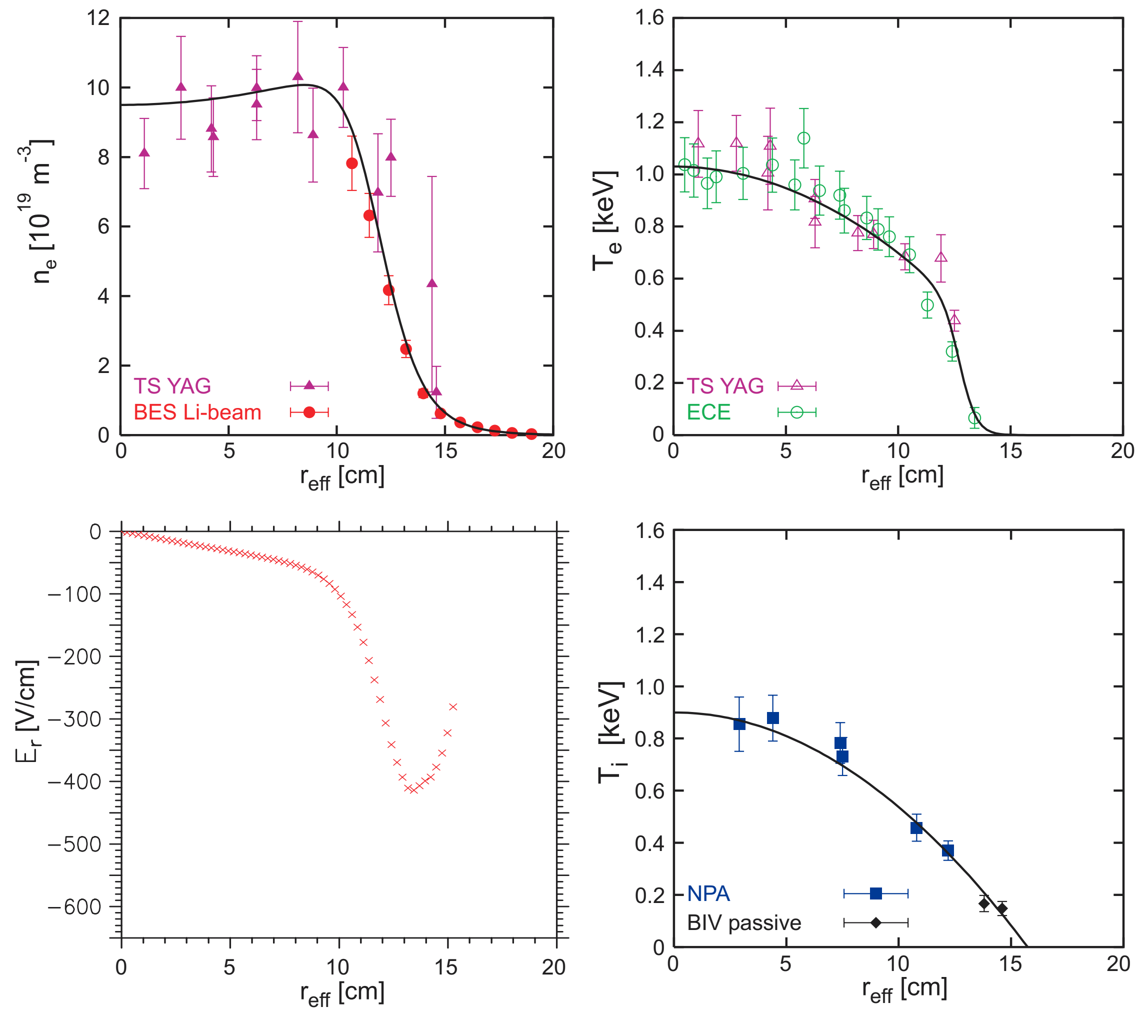

Figure 4. Profiles of n_e, T_e and T_i with fits used for calculations (#56688-93, t=0.2-0.3 s, $\bar{\iota} \approx 5/10$). E_r calculated by DKES is also shown.

The positive results of the experiment in the divertor configuration stress the Optimized Confinement regime as a possible option for an operational mode in Wendelstein 7-X. The positive results in the discharges with pure ECRH could be important for future experiments in W7-X, where only ECRH will be available for steady-state. However, the radiative losses (figure 3, green curve) are increasing on the timescale of the discharge. It is still not clear, how this behaviour will affect the OC regime with regard to the steady-state operation.

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