Current Balance Analysis at the W7-AS Stellarator
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Introduction: Due to the absence of the strong ohmic current small non-inductive
plasma currents can be investigated in Stellarators with a precision difficult to be achieved
in an equivalent Tokamak. In W7-AS, which has fairly low vacuum magnetic shear, the
rotational transform is modified by the non-inductive currents. Since the confinement
properties depend sensitively on the profile of the rotational transform [1], they are
influenced by the internal currents. The aim of this paper is to test the predictions of the
neoclassical theory for the current densities at W7-AS. As a first example the current
balance will be analyzed in detail for several purely ECR heated discharges. For these
discharges the internal bootstrap current is compensated by the induced ohmic one to
provide net current free conditions. Calculated profiles of current densities have not been
presented so far for W7-AS due to the lack of measured profiles of the effective charge
\( Z_{\text{eff}} \). Profiles of \( Z_{\text{eff}} \) can now be determined from the intensity of bremsstrahlung in the
near infrared.

Calculation of current density profiles: The total current density is assumed
to be a linear superposition of the ohmic and bootstrap component. The neoclassical
conductivity has been calculated by the DKES code [2]. For the determination of the ohmic
current density the experimental loop voltage has been used. Monoenergetic transport
coefficients of the bootstrap current have been calculated by DKES as well. A convolution
algorithm based on the Spitzer function results in the transport coefficients \( D_{31} \) and \( D_{32} \).
The coefficients are in good agreement with those from a Tokamak scaling (fit of the DKES
results for a database of Tokamak configurations) taking the reduction of the averaged
toroidal curvature of \( \kappa = 0.7 \) into account. Therefore the bootstrap current at W7-AS can
be regarded as 'Tokamak-like', and the bootstrap current density is given by

\[
\begin{align*}
  j_b^a &\simeq D_{31}^a (\nabla n_a / n_a - q_a E_r / T_a) + D_{32}^a \nabla T_a / T_a, \\
\end{align*}
\]

where \( q_a \) is the charge of particle species \( \alpha \).

The radial electric field \( E_r \) is calculated self-consistently from the ambipolarity condition \( \Gamma_e = \Gamma_i \) where the neoclassical fluxes are given by

\[
\Gamma_a = -n_a (D_{11}^a (\nabla n_a / n_a - q_a E_r / T_a) + D_{12}^a \nabla T_a / T_a). 
\]

\( D_{11} \) is the particle diffusion coefficient and \( D_{12} \) accounts for the temperature gradient
driven particle fluxes. Most important for the following are two special cases of the ambi-
polarity condition. For \( T_e \gg T_i \) there is \( \Gamma_e \approx 0 \) and a strongly positive \( E_r \) is predicted ('electron root'), for \( T_e \approx T_i \) ('ion root', described by \( \Gamma_i \approx 0 \) a strongly negative \( E_r \) may occur (see e.g. [1]). For both cases holds \( \nabla n_a / n_a - q_a E_r / T_a \approx D_{12}^a / D_{11}^a \nabla T_a / T_a \). Hence the bootstrap current can be approximated by:

\[
\begin{align*}
  j_b^a &\approx D_{31}^a (D_{32}^a / D_{31}^a - D_{12}^a / D_{11}^a ) \nabla T_a / T_a. \\
\end{align*}
\]

If no mixing of different transport regimes is assumed for the Stellarator long-mean-free-
path regime, calculations yield \( D_{12} / D_{11} = 1.25 \) (for the most important \( \sqrt{\nu} \)-regime) and
$D_{32} = D_{31}$ (for the banana regime in the 'Tokamak-approach'). The important consequences of this estimation are: i) the ion bootstrap current is suppressed by the negative $E_r$ due to the 'ion root' and is nearly negligible for W7-AS as will be shown below, ii) for the same reason the electron bootstrap current is enhanced by the negative $E_r$ due to the different sign of $q_n$, iii) the electron bootstrap current is strongly reduced in the plasma center if the 'electron root' feature occurs.

Figure 1: Profiles of $T_e$ and $n_e$ for $\#46616$ (squares: from Ruby Thomson scattering, dots: from YAG Thomson scattering, triangles: from ECE), right: profile of effective charge $Z_{\text{eff}}$

The calculations were performed using experimental profiles of $T_e$, $n_e$ and $Z_{\text{eff}}$. Profiles of $T_e$ and $n_e$ are taken from Thomson scattering (Ruby and YAG laser systems) and additional $T_e$ data from ECE. For the determination of the $Z_{\text{eff}}$ profile the intensity of bremsstrahlung has been measured at 1030 nm. $Z_{\text{eff}}$ profiles have been determined from the radiation profiles. The reconstruction method is described in [3].

**Results and discussion:** First, a discharge is discussed with an ECRH power of 200 kW and central electron temperature of about 1.5 keV at a central density of $4 \times 10^{19}$ m$^{-3}$. The measured profiles of electron temperature, density, and effective charge are shown in fig. 1. The $T_i$ profile has been calculated from power balance. The agreement of measured $T_i$ profiles and those calculated from power balance has been shown earlier [1].

The strong increase of $Z_{\text{eff}}$ for $r_{\text{eff}} \geq 14$ cm is an artefact due to the method of analysis and is not confirmed by spectroscopy. The effect of $Z_{\text{eff}}$ on the current densities was checked by keeping $Z_{\text{eff}}$ constant ($\approx 2$) for all $r_{\text{eff}}$. There is only a difference of about 5% between the ohmic and the bootstrap current calculated with the $Z_{\text{eff}}$ profile shown in fig. 1 and $Z_{\text{eff}}$ held constant, respectively.

The calculated radial electric field and current densities are shown in fig. 2. Although the ambipolarity condition has three solutions for the central region of the plasma up to $r=5$ cm, the strong positive solution (‘electron root’) is not reliable. Hence only the ‘ion root’ solution was taken into account for the analysis of the current balance. To check the reliability of the calculation, $E_r$ was estimated from the ambipolarity condition using transport coefficients for $E_r = 0$ (analytic model). Due to the strongly negative radial electric field in the gradient region of density and $T_i$ the ion bootstrap current is almost negligible ($\approx 0.1$ kA). The enhancement of the electron bootstrap current for $r > 10$ cm due to the negative $E_r$ can be assessed by comparison with the calculation for $E_r = 0$. As expected, the contribution of the ohmic current is most important near the plasma center and the bootstrap current contributes most at the outer region of the plasma.
Calculation of the total currents gives -3.11 kA for the ohmic and 4.33 kA for the bootstrap component. The remaining discrepancy of 1.22 kA might be due to an additional ECR driven current (ECCD) which can not be fully excluded for the conditions of this discharge. Besides, the theoretical model of the bootstrap current may be improved. The model applied so far can produce an error of about of about 10 % for the bootstrap current density [4].

![Graph](image)

Figure 2: Left: Radial electric field, calculated with the DKEE-code (crosses) and with the analytic model (dash dotted). Right: current density profiles: ohmic (dots, negative), bootstrap for \( E_r = 0 \) (dots, positive), for the analytic model (dash dotted) and for the ion root (full)

As a second example a density scan will be discussed which was performed at maximum ECRH power of 1.2 MW. The profiles of electron temperature and density have already been published [5]. The central density varied from \( 1.7 \times 10^{19} \text{m}^{-3} \) to \( 7.2 \times 10^{19} \text{m}^{-3} \), the central electron temperatures from 6 keV to 3 keV, respectively. \( Z_{\text{eff}} \) profiles have been estimated for the discharges with central \( n_e > 3 \times 10^{19} \text{m}^{-3} \). For the discharge with the lowest density, a constant \( Z_{\text{eff}} = 3.7 \) was assumed since \( Z_{\text{eff}} \) increases as \( n_e \) becomes smaller.

The calculated radial electric field and the current densities are shown in fig.3 for the discharge at \( n_e(0) = 3.5 \times 10^{19} \text{m}^{-3} \) (see also [6]). At the central region of the plasma a strong positive \( E_r \) exists (‘electron root’) followed by a region where three or even five solutions of the ambipolarity condition exist (‘ion root’ and additional unstable roots). The radial electric field plays a crucial role for the bootstrap current density. Again the negative electric field at the outer plasma region reduces the ion bootstrap current which is negligibly small. If the calculations are performed with \( E_r = 0 \) or with the analytical model for \( E_r \), the electron bootstrap current will be strongly overestimated for the inner region of the plasma. The discrepancy of the total current balance is more than 15 kA for \( E_r = 0 \). If the strong positive \( E_r \) is taken into account over the whole range where the ‘electron root’ exists the bootstrap current is extremely reduced. The total is underestimated in this case, but nevertheless the current balance can only be understood if the electron root at the inner region of the plasma exists. For the calculation of a realistic bootstrap current density profile the transition from electron to the ion root has to be estimated by means of a thermodynamic energy principle [7].

The region where the strongly positive \( E_r \) exists extends up to more than half of the plasma radius for the discharge with the lowest density. For higher densities this region gets smaller until the ion root exists up to the center of the plasma. Nevertheless the influence of the electron root can not be excluded even for the highest central density of \( 7 \times 10^{19} \text{m}^{-3} \). For all of the discharges of the density scan temperature profiles are very similar in the
outer region of the plasma where the electron bootstrap current is not suppressed. Due to its 'Tokamak-like' behaviour it is therefore expected that the total bootstrap current increases (for pure 'banana-regime' conditions). According to this prediction the total bootstrap current (taking $E_r$ into account) increases with density. The increase is nearly linear for the discharges with low density and nearly saturates for the highest density.

Summary: The internal current density profiles and the current balance have been analyzed for various purely ECR heated discharges at W7-AS in order to check the predictions of the neoclassical theory. The radial electric field significantly influences the current density profiles. As a consequence, the ion bootstrap current is almost negligible for the experimental conditions at W7-AS. For a discharge with moderate central electron temperature a quite good balance has been achieved for calculated total ohmic and bootstrap current, in agreement with the net current free experimental conditions. To assess the reliability of the neoclassical predictions, further analysis of a large number of similar discharges will be needed. For discharges with very high central electron temperature, the electron bootstrap current is strongly reduced in the inner region of the plasma due to the strongly positive radial electric field. Furthermore, the time dependence of those discharges must be taken into account for the calculation of current density profiles because the time constant for the diffusion of the loop voltage is of the order of some 100 ms.

References