26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 1489 - 1492

Current Balance Analysis at the W7-AS Stellarator

C. Wendland, U. Gasparino, H. Maaßberg, E.R. Solano, and the W7-AS Team
Max-Planck Institut für Plasma Physik,
EURATOM Association, D-85748 Garching, Germany

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 neoclassial 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_{eff}. Profiles of Z_{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

$$j_b^\alpha \simeq D_{31}^\alpha(\nabla n_\alpha/n_\alpha - q_\alpha E_r/T_\alpha) + D_{32}^\alpha \nabla T_\alpha/T_\alpha, \tag{1}$$

where q_α is the charge of particle species α.

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

$$\Gamma_\alpha = -n_\alpha(D_{11}^\alpha(\nabla n_\alpha/n_\alpha - q_\alpha E_r/T_\alpha) + D_{12}^\alpha \nabla T_\alpha/T_\alpha). \tag{2}$$

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 ambipolarity 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 $\nabla n_\alpha/n_\alpha - q_\alpha E_r/T_\alpha \approx D_{12}^\alpha/D_{11}^\alpha \nabla T_\alpha/T_\alpha$. Hence the bootstrap current can be approximated by:

$$j_b^\alpha = D_{31}^\alpha(D_{32}^\alpha/D_{31}^\alpha - D_{12}^\alpha/D_{11}^\alpha)\nabla T_\alpha/T_\alpha. \tag{3}$$

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_α, iii) the electron bootstrap current is strongly reduced in the plasma center if the 'electron root' feature occurs.

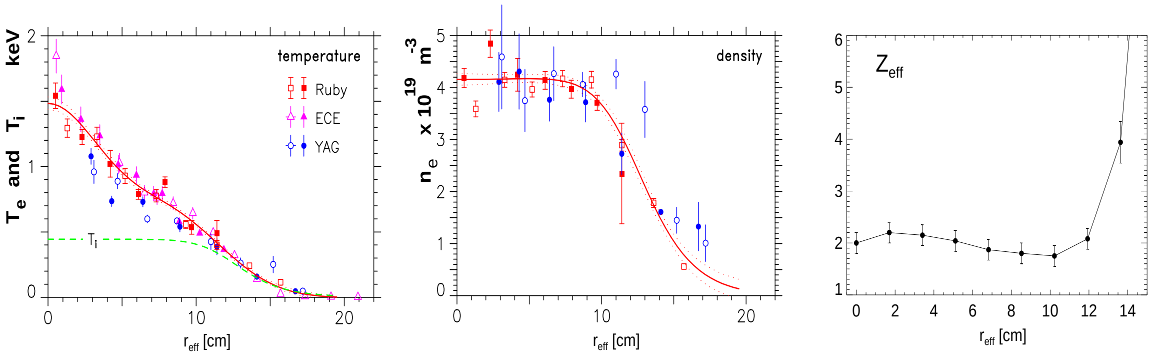

Figure 1: *Profiles of T_e and n_e for #46616 (squares: from Ruby Thomson scattering, dots: from YAG Thomson scattering, triangles: from ECE), right: profile of effective charge Z_{eff}*

The calculations were performed using experimental profiles of T$_e$, n$_e$ and Z$_{eff}$. 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$_{eff}$ profile the intensity of bremstrahlung has been measured at 1030 nm. Z$_{eff}$ 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 200kW and central electron temperature of about 1.5 keV at a central density of 4 × 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_{eff} for r_{eff} >14cm is an artefact due to the method of analysis and is not confirmed by spectroscopy. The effect of Z_{eff} on the current densities was checked by keeping Z_{eff} constant ($\approx$ 2) for all r_{eff}. There is only a difference of about 5% between the ohmic and the bootstrap current calculated with the Z_{eff} profile shown in fig. 1 and Z_{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=5cm, 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> 10cm 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].

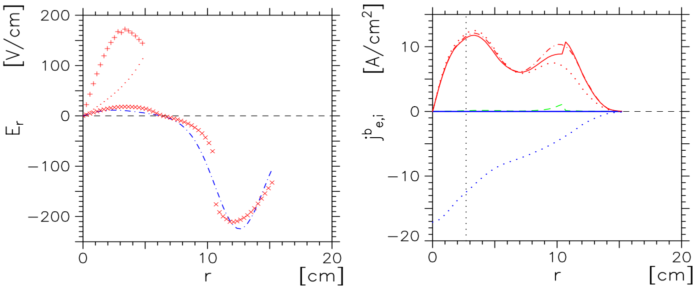

Figure 2: *Left: Radial electric field, calculated with the DKES-code (crosses) and with the analytic model (dash dotted). Right: current density profiles: ohmic (dots,negative), bootstrap for* $E_r = 0$ *(dots,positive), for the analytic model (dash dotted) and for the ion root (full)*

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 $1.7 \times 10^{19}\mathrm{m}^{-3}$ to $7.2 \times 10^{19}\mathrm{m}^{-3}$, the central electron temperatures from 6 keV to 3keV, respectively. Z_{eff} profiles have been estimated for the discharges with central $n_e > 3 \times 10^{19}\mathrm{m}^{-3}$. For the discharge with the lowest density, a constant $Z_{eff} = 3.7$ was assumed since Z_{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 $n_e(0) = 3.5 \times 10^{19}\mathrm{m}^{-3}$ (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 15kA 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 $7 \times 10^{19}\mathrm{m}^{-3}$. For all of the discharges of the density scan temperature profiles are very similar in the

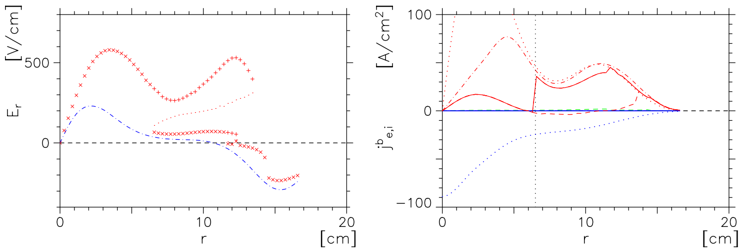

Figure 3: *Left: Radial electric field, calculated with the DKES-code (crosses) and with the analytic model (dash dotted). Right: current density profiles: ohmic (dots,negative), bootstrap for* $E_r = 0$ *(dots,positive), for the electron root (dashed), for the analytic model (dash dotted) and for both roots with assumed transition (full curve).*

outer region of the plasma where the electron bootstrap current is not supressed. 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

[1] Brakel R et al 1997 Plasma Phys. Control. Fusion **39** B283

[2] van Rij W I and Hirshman S P 1989 Phys Fluids B **1** 563

[3] Zoletnik S and Kalvin S 1993 Rev.Sci.Instr. **64**(5) 1208

[4] Solano E et al 1998 Proc. 25th EPS Conf.Contr.Fusion Plasma Physics (Prague,1998) vol 22C, ed P.Pavlo (Geneva:EPS), p 1718

[5] Kick M et al 1999 Plasma Phys. Control. Fusion **41** A549

[6] Fuchs C et al, this conference

[7] Maaßberg, H Burhenn R, Gasparino U, Kühner G, Ringler H and Dyabilin K S 1993 Phys. Fluids B **5** 3627