

Toroidal Current Densities Viewed by Magnetic Diagnostics at W7-AS

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Introduction: In stellarators, no parallel currents are needed to produce the plasma confining field. An ideal stellarator plasma would carry only the diamagnetic current density which is necessary to satisfy the radial force balance and the Pfirsch-Schlüter (PS-) currents. The latter flow toroidally and keep the joint current density divergence free. Toroidicity leads to a dipole structure of the PS-currents. Although the net toroidal current is zero, they create a poloidal field which modifies the equilibrium configuration depending on the plasma- β . One part of stellarator optimisation, like in W7-X, can be to minimise these internal current densities.

Dissipative effects and plasma heating drive currents along magnetic field lines such as neoclassical bootstrap-, NBI- and EC-driven currents. Although the net toroidal current in W7-AS can be forced to vanish using an OH transformer, the internal net toroidal current *densities* do generally *not* cancel, thus influencing the magnetic configuration.

Net toroidal current densities can be inferred from neoclassical transport or power deposition calculations, given temperature, density and Z_{eff} -profiles [1]. The resulting external magnetic fields can be calculated using the 3D-MHD equilibrium code NEMEC [2] and the DIAGNO [3] post-processing package or a current filament model.

Experimental: The poloidal magnetic field produced by the toroidal current density is measured using four coils with a winding density of $n_w = 10\text{cm}^{-1}$ and a cross section $A = 2.69\text{cm}^2$. The signals are preprocessed by integrators with an effective integration time $\tau = 0.1\text{ms}$. The measured voltages U_k are given by $U_k \cdot \tau = \Phi_k = A \cdot n_w \int_0^{L_k} \vec{B} \cdot d\vec{l}$ with L_k the length of coil k and Φ_k the flux through each coil. Data are sampled with a 12 bit ADC at 1kHz.

The signals U_k have to be 'cleaned' very carefully from parasitic signals due to even small variations ΔI of modular coil current, corner coil current, vertical field and OH field coil currents. Transfer functions describing these effects have been determined experimentally. After stray field subtraction a software drift compensation is performed which finally allows to measure fluxes of $40\mu\text{Wb}$ with a precision of 10%.

Simulations: In order to calculate expected magnetic fluxes we have implemented a routine to deduce current densities from experimental profiles, including temperature, density and effective charge Z_{eff} .

The bootstrap current density j_{NC} and neoclassical conductivity σ_{NC} are obtained from a fit published by *Sauter et al.* [4] which is based on neoclassical calculations for various tokamak equilibria. Since the net toroidal current I_{tor} is a control parameter of W7-AS, we adapt the ohmic current density j_{OH} so as to achieve the measured value of I_{tor} . The profile of j_{OH} is determined by σ_{NC} .

The magnetic field at the coil locations is calculated either by DIAGNO or by a straight/circular current filament model (SCFM/CCFM). For the latter, the current den-

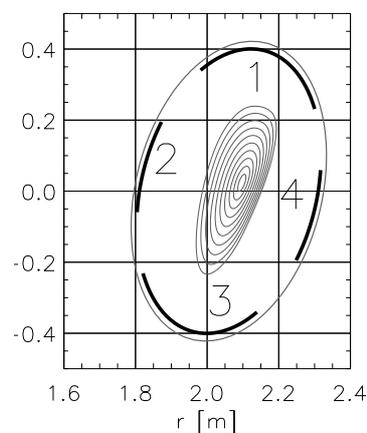


Figure 1: coils used to measure poloidal magnetic fluxes

sity distribution is converted to a current distribution on a grid of points equidistant in “magnetic” coordinates r_{eff} and θ^* which are provided by NEMEC. In addition to j_{NC} and j_{OH} , the PS current density has to be determined from the profiles as well:

$$j_{PS} = 0.7 \cdot \frac{2}{\iota B_o} \cdot \nabla p \cdot \cos\theta \quad (1)$$

where p is the pressure, B_o the toroidal field, ι is the rotational transform and θ the poloidal angle. The factor 0.7 describes the current reduction due to W7-AS optimisation.

In addition to the “realistic” distributions based on experimental plasma profile data a variety of ad-hoc current density distributions were used in order to evaluate the theoretical possibilities of the diagnostic. Differently peaked profiles were used as well as hollow profiles with varying radial position of the maximum current density or PS-like distributions.

In order to allow easier interpretation of the measurements, we use four linear combinations instead of the raw signals:

$$\Delta\Phi_o = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 = I_{tor} \cdot 0.225 \mu Wb/A \quad (2)$$

$$\Delta\Phi_{cos} = \Phi_1 - \Phi_2 - \Phi_3 + \Phi_4 \quad (3)$$

$$\Delta\Phi_{sin} = \Phi_1 + \Phi_2 - \Phi_3 - \Phi_4 \quad (4)$$

$$\Delta\Phi_{cos2} = -\Phi_1 + \Phi_2 - \Phi_3 + \Phi_4 \quad (5)$$

The $\Delta\Phi_o$ signal yields the net current, the 4 coils “in series” work as a Rogowski coil.

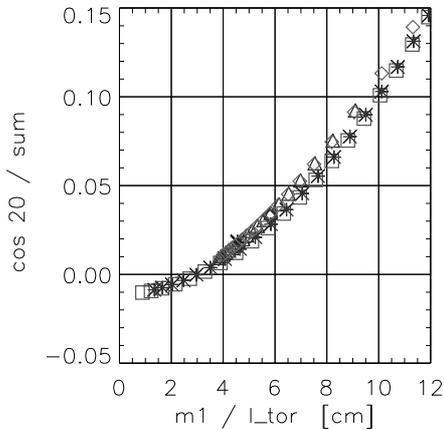


Figure 2: $\Delta\Phi_{cos2}/\Delta\Phi_o$ as a function of the moment $m1$ eq.(6) divided by I_{tor}

For nonzero net current I_{tor} , the $\Delta\Phi_{cos2}$ signal divided by $\Delta\Phi_o$ is roughly proportional to $m1$ divided by I_{tor} , where

$$m1 = \int_0^a j(r) r^2 dr, \quad (6)$$

r is the effective radius and a the minor plasma radius. The $\Delta\Phi_{cos2}$ combination yields zero signal if the current flows on axis, it increases as currents flow closer to the plasma boundary, i.e. it is sensitive to PS currents as well. NEMEC/DIAGNO calculations indicate a weakly quadratic scaling of $\Delta\Phi_{cos2}$ with the kinetic energy and hence with PS currents.

The 260 simulations with our SCFM/CCFM model show that the $\Delta\Phi_{cos}$ signal measures the dipole moment of the current distribution, *i.e.* mainly the PS currents. Analysis of 280 NEMEC equilibria with a vacuum rotational transform between $\iota = 0.32 \dots 0.38$ and $B_0 = 2.5T$ confirms this result. The $\Delta\Phi_{cos}$ signal obtained by NEMEC/DIAGNO is a linear function of the kinetic energy W with a slope of $27.2 \mu Wb/kJ$, if other than PS currents are neglected. A direct comparison of fluxes obtained from NEMEC/DIAGNO and from the CCFM model showed good agreement.

The $\Delta\Phi_{sin}$ signal senses vertical or horizontal shifts and is extremely sensitive to slight rotations of the PS-current’s dipole structure.

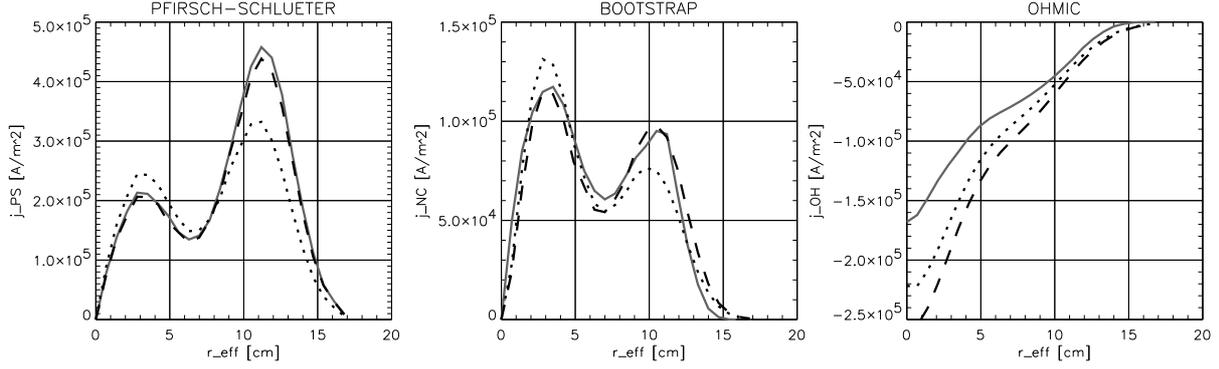


Figure 3: current densities used for the 3 simulations. sim1: dotted, sim2: dashed, sim3: solid curves. left: j_{PS} , middle: j_{NC} , right: j_{OH}

Comparison of Calculations and Experiment: For an ECR heated discharge (# 46616, $t \approx 0.346$, $B_0 = 2.5T$) we compare measurements to CCFM simulations using experimental T_e , n_e and Z_{eff} profiles provided by the YAG Thomson diagnostic, $T_i(0)$ and approximate values of the current densities, assuming

- sim1: $n_i = n_e / Z_{\text{eff}}$, $T_i = T_i(0) / T_e(0) \cdot T_e$
- sim2: $n_i = n_e \cdot (1 - (Z_{\text{eff}} - 1) / (Z_{\text{imp}} - 1))$, $T_i = T_i(0) \cdot n_e / n_e(0)$, $Z_{\text{imp}} = 6$
- sim3: j_{NC} , j_{OH} , j_{PS} and n_i , T_i profiles from neoclassical calculations [1]

In fig. 3 the different current densities are shown. The ohmic current from the neoclassical calculation was too low to compensate the bootstrap current. This has been adjusted in our simulation sim3 in order to match the experimental value of $I_{\text{tor}} = 0$. The bootstrap current densities obtained from sim2 and the neoclassical calculation are almost identical. Differences between the three calculations are mainly due to different pressure gradients, which is obvious from the PS current density, eq.(1). Compared to experimental data, sim2 and sim3 seem to slightly overestimate the PS current density (see fig.3) and hence the kinetic energy deduced from the profiles. This is also evident from fig.4 where simulated and experimental signals $\Delta\Phi_{\text{cos}}$ and $\Delta\Phi_{\text{cos}2}$ are compared. The agreement between sim1 and experiment is excellent, although the kinetic energy derived from the profiles used for the sim1 $j-$ values is too low, as can be seen from the table below.

The table compares $\Delta\Phi_{\text{cos}}$ obtained from experiment, the three simulations and from the NEMEC scaling for PS currents (see above) with kinetic energy W for discharge # 46616 at $t = 300\text{ms}$.

signal	experiment	sim 1	sim 2	sim 3
$\Delta\Phi_{\text{cos}}[\mu\text{Wb}]$	-158.620	-152.501	-195.778	-208.503
$\Delta\Phi_{\text{cos}}\text{PS}[\mu\text{Wb}]$	-	-167.431	-216.342	-223.096
NEMEC $\Delta\Phi_{\text{cos}}\text{PS}[\mu\text{Wb}]$	-153.868	-135.117	-174.496	-180.023
$W[\text{J}]$	5800.	5092.63	6580.78	6790.41

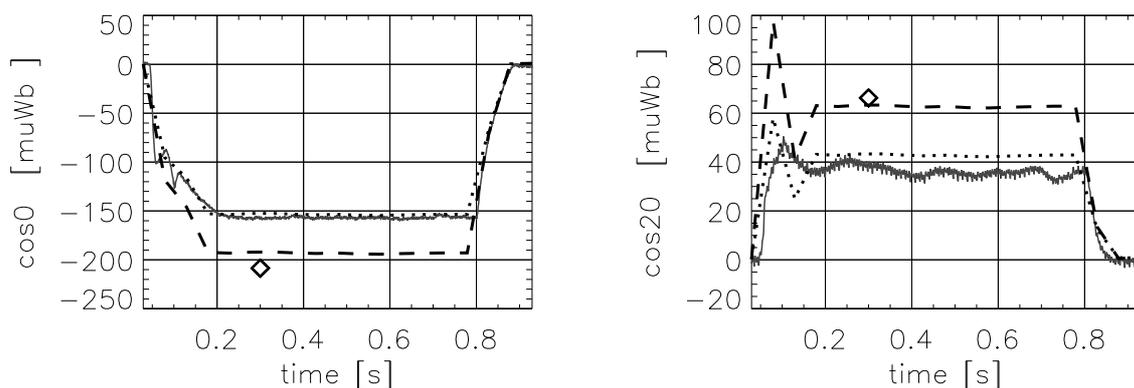


Figure 4: *Experimental and simulated fluxes $\Delta\Phi_{cos}$ and $\Delta\Phi_{cos2}$ for discharge # 46616. light grey: measurement, dots: sim1, dashes: sim2, diamond: sim3*

Conclusions: Variations of internal current densities **can** be measured using linear combinations of the four coil signals. PS currents are measured by the $\Delta\Phi_{cos}$ and $\Delta\Phi_{cos2}$ combinations. The $\Delta\Phi_{cos2}$ measures $m1 = 2 \pi \int_0^a j(r) r^2 d r$.

The experimental fluxes can be used to check consistency with calculated current densities. Coarse features of the time evolution of the measured signals can be reproduced using experimental profiles and a simple model. Differences between theory and measurement of 20-30% are mainly due to calculated PS currents. In order to resolve finer details we would need to have a more precise model. The main difficulty of our CCFM probably is the ∇p and hence the j_{PS} calculation, as well as lacking information on ion temperature and density profiles. For short discharges or very high electron temperatures current diffusion calculations might be necessary.

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