High Power ECCD Experiments at W7-AS

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Abstract: At the W7-AS stellarator, high power electron cyclotron current drive (ECCD) experiments are analyzed. In these net-current-free discharges, the ECCD as well as the bootstrap current are feedback controlled by an inductive current. Based on measured profiles, the neoclassical predictions for the bootstrap and the inductive current densities as well as the ECCD from the linear adjoint approach with trapped particles included are calculated, and the current balance is checked. Launch-angle scans at fixed density as well as density scans at fixed launch-angle are described.

1. Introduction

External plasma current feedback is mandatory in stellarators to control the radial position of low-order rational values in the rotational transform profile. For example, the island divertor concept is based on the island position control which is affected both by the bootstrap current and by the Pfirsch-Schlüter currents. Since large stellarators lack an inductive transformer, electron cyclotron current drive (ECCD) may be a potential tool in case of bootstrap and Pfirsch-Schlüter currents being significantly reduced by the stellarator optimisation [1,2] concept as is the case for W7-X (under construction at Greifswald).

ECCD experiments at W7-AS with about 1.3 MW power are analyzed. The total plasma current was feedback controlled by the inductive transformer in order to obtain stationary conditions (the L/R-time is on the order of 1 second) and to avoid the effect of low-order rational values at the plasma edge degrading the confinement properties. In these experiments, 2nd harmonic X-modes at 140 GHz (corresponding to $B \simeq 2.5$ T) were launched from the low-field side by 3 gyrotrons using a flexible mirror system. In the W7-AS "standard" configuration, a significant number of trapped particles exists in the ECRH launching plane. By increasing the current in the special coils at the "launching plane", a "maximum-B" scenario without trapped particles in this plane can be realized.

2. Analysis of ECCD Experiments

The estimation of the electron cyclotron driven current from the current balance must rely on the accurate calculation of both the bootstrap and the inductive current densities which depend on the n_e, T_e and $Z_{\rm eff}$ profiles. For the stationary phase of each discharge, these profiles are obtained from the ECE as well as the Ruby- and YAG-Thomson scattering diagnostics. With these profiles, both the bootstrap current density, j_b, and the inductive current density, $j_{\rm ind}$, are estimated from the neoclassical transport matrix obtained from DKES code [3] calculations for the W7-AS magnetic configurations. The generation of a DKES database of the 3 mono-energetic transport coefficients with respect to radius, r, collisionality, ν/v, and radial electric field, E_r, for a specific magnetic configuration is very time consuming [4]. Thus, the bootstrap current coefficients are calculated only for a fixed rotational transform profile, $\iota(r)$, and a self-consistent (iterative) treatment in which j_b depends on the total current density profile is omitted (see Sec. 3). The Lorentz form of the pitch-angle collision term used in DKES does not conserve momentum, and a

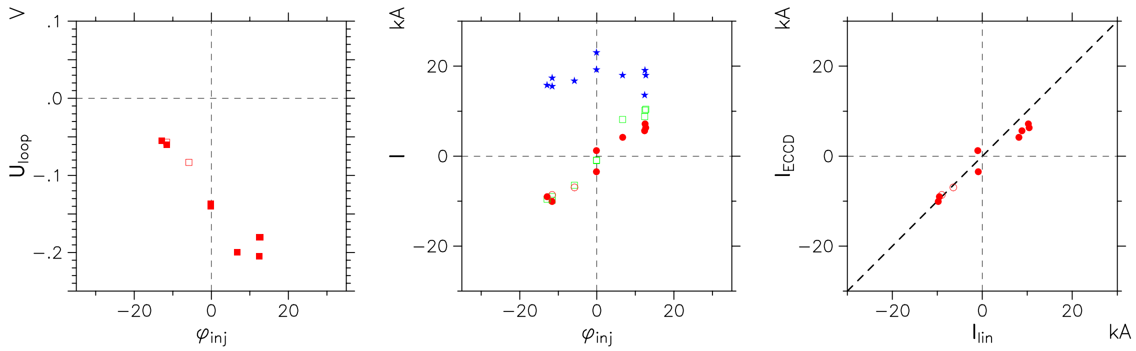

FIG. 1: ECCD (1.3 MW power) launch-angle scan at $n_e \simeq 6.0 \cdot 10^{19}$ m^{-3} in "standard" configuration: U_l vs. $\varphi_{\rm inj}$ (left); bootstrap current, I_b ($\star$), $-I_b - I_{\rm ind}$ (●, ○) and the linear prediction, $I_{\rm lin}$ (□) vs. $\varphi_{\rm inj}$ (in the center), and $I_{\rm ECCD} = -I_b - I_{\rm ind}$ vs. $I_{\rm lin}$ (right).

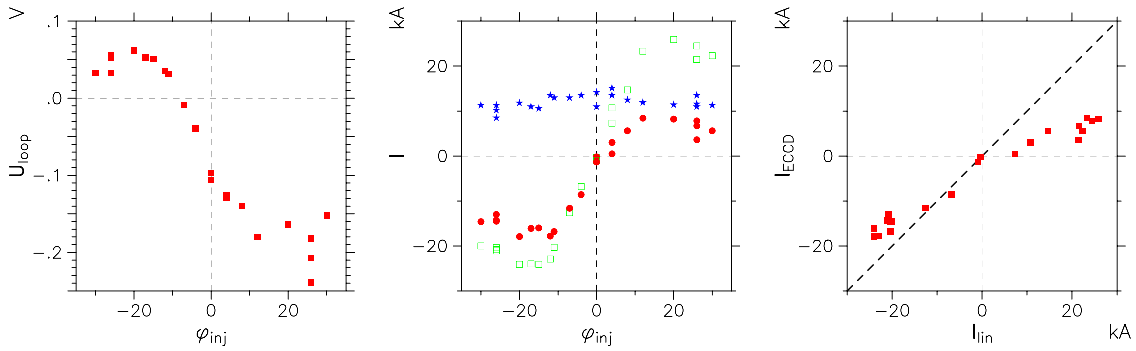

FIG. 2: ECCD (1.3 MW power) launch-angle scan at $n_e \simeq 2.5 \cdot 10^{19}$ m^{-3} in "standard" configuration; comp. FIG. 1.

simplified "local" correction based on Spitzer's function is used in the energy convolution [5] of both the bootstrap coefficient and the electric conductivity coefficient.

For evaluating the bootstrap current density, the radial electric field is estimated from the ambipolarity condition of purely neoclassical fluxes, i.e., the additional "anomalous" contributions dominating at outer radii are assumed to be intrinsically ambipolar. Especially in the low density ECRH discharges, highly peaked central T_e-profiles can be found [4]. In this central region, the ambipolarity condition leads to the "electron root" feature with strongly positive E_r significantly improving the electron confinement (transition from the $1/\nu$- to the $\sqrt{\nu}$-regime in the stellarator neoclassical theory). The "convective" transport of the ripple-trapped suprathermal electrons generated by the ECRH absorption can play an important role in establishing this "electron root" feature. In this region, the predicted j_b^e is strongly reduced. The "electron root" region estimated in this way shows a tendency to be broader compared to the central peaking of the T_e-profile and the region of fast decay after switching off the ECRH; see [4]. Even an "electron root" feature can be obtained being in conflict with the electron energy balance. For such cases a lower limit for E_r may be obtained from the ambipolarity condition with particle transport coefficients at $E_r = 0$ to get a careful correction.

An estimate of the ECCD density from linear theory is obtained from the adjoint approach with trapped particles effects included [5]. In the "collisionless" limit used for estimating the ECCD, only the passing particles contribute to the current (the distribution function of all trapped electrons is symmetric in $v_{||}$). Consequently, the fraction of electrons carrying

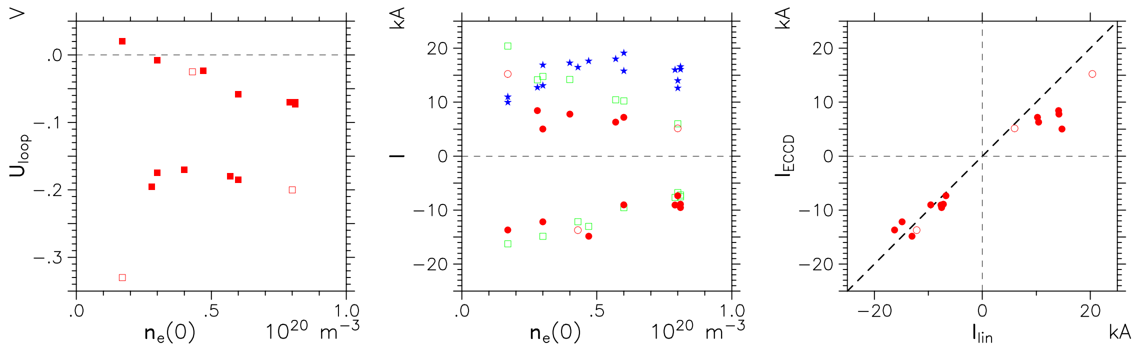

FIG. 3: ECCD (1.3 MW power) density scan at $\varphi_{\rm inj} = \pm 13^\circ$ in "standard" configuration; see FIG. 1.

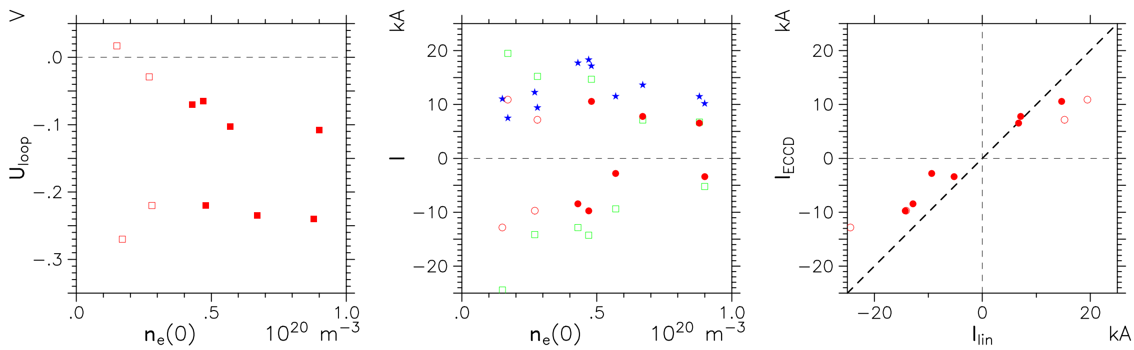

FIG. 4: ECCD (1.3 MW power) density scan at $\varphi_{\rm inj} = \pm 13^\circ$ in "maximum-B" configuration; see FIG. 1.

the current, $f_p = 1 - f_t$, is reduced, and the friction between passing and trapped electrons further decreases the ECCD. This linear prediction is implemented in the ray-tracing code which is used to calculate the power deposition and the ECCD density profiles.

ECCD currents roughly up to ±20 kA are obtained from the current balance of bootstrap (I_b) and inductive currents ($I_{\rm ind}$), i.e. $I_{\rm ECCD} = -I_b - I_{\rm ind}$, in the net-current free discharges. For an ECRH launch-angle scan at moderate density ($n_e = 6 \cdot 10^{19}$ m^{-3}), the linear prediction agrees well with the current balance for the "standard" configuration (with trapped particles in the launching plane); see Fig. 1. An equivalent scan at low density shown in Fig. 2 ($n_e = 2.5 \cdot 10^{19}$ m^{-3}), however, yields less ECCD currents from the current balance compared to the linear prediction. Especially for co-ECCD, the "experimentally" found current is smaller by a factor of more than 2. In both scans, the estimated I_b is only weakly dependent on the launch angle, $\varphi_{\rm inj}$, since the T_e and n_e profiles at outer radii leading to the main contribution to I_b are very similar. Furthermore, the good balance of bootstrap and inductive current calculated neoclassically based on the experimental profiles for small $\varphi_{\rm inj}$ confirms these estimates also for the ECCD scenarios.

These ECCD results are supported by density scans at fixed launch angles for co- and counter-ECCD, $\varphi_{\rm inj} = +13^\circ$ and -13°, respectively. For the "standard" configuration in Fig. 3 and the "maximum-B" configuration in Fig. 4, fairly good agreement of the linear prediction with the current balance is obtained at higher densities for co- and counter ECCD. At lower densities, however, the adjoint approach overestimates the ECCD compared to the current balance. For the very low densities, the evaluation of all currents is affected by a fairly strong uncertainty of the $Z_{\rm eff}$ values.

3. Discussion and Conclusions

In the counter-ECCD cases, the central T_e-profiles are "clipped", and also the n_e-profiles are very flat. In particular at low densities, the estimation of the ι profile based on the bootstrap and inductive current density estimates as well as on an ECCD profile which fulfils the constraint $I_{\rm ECCD} = -I_b - I_{\rm ind}$ leads to $\iota \simeq 0$ roughly at a radial position where the $T_e(r)$ is clipped (i.e. $T_e' \simeq 0$). A reasonable *hypothesis* may be the assumption that at very low ι-values ergodisation appears. In this region, the energy confinement is lost, and also the ECCD profile flattens. So far, no MHD activity is observed under these conditions. On the other hand, there are no indications for $\iota < 0$ with confinement. DKES calculations with a fixed Fourier spectrum of B, but with varied ι show that the bootstrap current coefficient for W7-AS is fairly similar to the coefficient of an equivalent tokamak, i.e., a clear $1/\iota$ dependence is obtained in the *lmfp*-regime. Whereas the "stellarator-specific" ripple-trapped particles lead to a j_b contribution independent of ι, the particles being reflected at the maximum of B on the flux surface reflect the ι dependence quite similar as the tokamak bananas. A "self-consistent" modelling, where the tokamak-like ι-dependence is taken into account, shows that the region with $\iota \simeq 0$ is slightly broadened, but I_b is fairly weakly affected.

In the co-ECCD scenarios, the central ι can be fairly large due to the highly localized deposition profile. The strong inductive current with $j_{\rm ind} < 0$ dominates at intermediate radii whereas j_b can overcompensate $j_{\rm ind}$ at outer radii. ι-simulations for such conditions (again with the $I_{\rm ECCD} = -I_b - I_{\rm ind}$ constraint on the ECCD profile) can lead to $\iota = \frac{1}{2}$ once and $\iota = \frac{1}{3}$ twice in the profile (the edge value is slightly above $\frac{1}{3}$ for all discharges of these scans). In the ECE profile, a very strong $m = 2$ mode (identified by Mirnov data) is observed roughly at the position with $\iota = \frac{1}{2}$ in the simulations. At outer radii, two $m = 3$ modes corresponding to $\iota = \frac{1}{3}$ are found (supported by SX data) which are locked to the strong $m = 2$ mode. In these scenarios, the outer ι-profile with the dominant contribution to I_b is fairly flat, and the simplified approach with fixed $\iota(r)$ in the DKES database is justified.

The linear adjoint approach used for estimating the ECCD is tested with respect to the "collisionless" and the "collisional" limits for the (parallel) electric conductivity. Here, $\sigma_{||}$ normalized to the "collisional" Spitzer-Haerm value is reduced for the W7-AS "standard" configuration at 10 cm radius to 0.6 in the "collisionless" limit, $\nu \rightarrow 0$. This value is fairly similar for the equivalent circular tokamak. Both the DKES estimate for W7-AS and the Hinton-Hazeltine model show that $\sigma_{||}$ is just inbetween the limiting cases for the experiments under consideration. The collisionalities are high enough that also the barely-trapped electrons with the long bounce time contribute to the current, i.e., the distribution function of these barely-trapped electrons is not symmetric with respect to $v_{||}$. The corresponding reduction of the ECCD efficiency in the "collisionless" limit is even stronger compared to $\sigma_{||}$ since slightly suprathermal electrons with $v_{||} \sim v_\perp$ mainly contribute to the ECCD for optimum $\varphi_{\rm inj}$. For typical conditions of W7-AS, an ECCD efficiency reduction of about 0.4 is found. Consequently, $I_{\rm lin}$ estimated by the "collisionless" adjoint approach is a lower limit, and the discrepancy in the current balance will be even larger.

For the highly peaked power deposition, a quasi-linear formulation of the absorption can fail. Non-linear effects dominate especially for electrons with small $v_{||}$ [6]. For the ECCD scenarios at higher $\varphi_{\rm inj}$, however, the non-linear effects on the absorption as well as on ECCD are less important (a slight non-linear broadening of the absorption can be omitted with respect to the ECCD efficiency).

Non-linear bounce-averaged Fokker-Planck simulations [7] for the ECCD in a narrow central region are performed. The bounce-averaging procedure is identical to the "collisionless" adjoint approach with respect to the ECCD estimation for very low power levels (both codes are benchmarked). For the high power levels, a "stellarator-specific" loss-cone model describing the convective power sink due to the radial ∇B-drift of the ripple-trapped electrons is used. The highly peaked ECRH power deposition (corresponding to a toroidally averaged power density of about 50 W/cm^3) is formulated by a quasi-linear diffusion term where the diffusion coefficient $Q_{\perp\perp}^{ql}$ is obtained from the ray-tracing calculations. In the electron distribution function, a pronounced quasi-linear plateau is formed close to the relativistic resonance condition in combination with strong gradients allowing for the diffusive power flux due to collisions into the loss-cone. Although the deviation from the Maxwellian is farily strong for the low densities, the electric resistivity is only weakly affected. Furthermore, the ECCD efficiency depends only weakly on the heating power. Since the bootstrap current contribution from the deposition region is negligible (if the ambipolar radial electric field is taken into account), this kind of Fokker-Planck simulations with the "convective" loss-cone model cannot explain the deviation of the linear prediction (based on a Maxwellian) from the current balance. Quite different results, however, are obtained for an isotropic power-loss model which also leads to momentum loss. At low power levels, both models give identical results. With higher power the ECCD efficiency drops significantly. A physical picture for this momentum loss (current diffusion) is still missing.

In the Fokker-Planck calculations with the "convective" loss-cone model, very strong gradients (with respect to $v_{||}$) of the distribution function close to the loss-cone boundary are obtained, especially at low densities. The hypothesis of a kinetic instability in such cases is under investigation.

At high ECRH power levels, the ECCD obtained from the balance of bootstrap and inductive currents is smaller than the ECCD predicted from the linear "collisionless" adjoint approach with trapped particles taken into account. The error in the current balance decreases at higher densities. It seems to be unlikely that this discrepancy can be attributed to the unaccurate treatment of the bootstrap or the inductive currents. Fokker-Planck simulations show strong deviations from the Maxwellian, but cannot resolve this discrepancy.

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