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Fokker-Planck Estimation of Electron Distribution Functions for High Power ECCD at W7-AS

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Introduction

As a means of non-inductive current drive, electron cyclotron current drive (ECCD) is an important scheme for future superconducting stellarator experiments where ohmic current drive is no longer available, like in the Wendelstein 7-X experiment whose construction is under way in Greifswald, Germany. Although ideal stellarators don't need current drive, it is a good mean for control of the boundary value of the rotational transform and thus of the boundary structure and adds, moreover, to the experimental flexibility. To reach a good current drive efficiency, one has also to think about advanced current drive scenarios, like high field launch. In any case, the high power ECRH (already 50 Wcm^{-3} at present in Wendelstein 7-AS) required will distort the electron distribution function so that the usual quasi-linear theory may be not longer reliable and new approaches have to be made.

Experiments

In order to understand ECCD by high power ECRH, experiments at Wendelstein 7-AS with up to 1.3 MW ECRH input power at 140 GHz ($2nd$ harmonic X-mode for $B =$ 2.5 T) have been performed. Tiltable mirrors in the microwave launching system allow for significant co- and counter-current drive (with respect to increasing ι, same direction as bootstrap current). Driven currents up to ±20 kA are obtained from the current balance of bootstrap (I_{bt}) and ohmic currents (I_{oh}), i.e. $I_{bt} + I_{ECCD} = -I_{oh} \equiv -U_{loop}/R$, in the net-current free discharges assuming stationarity (see C. Wendland et al., this conference). The electron densities were in the range of $2.5 \cdot 10^{19}\ m^{-3}$ and electron temperatures of up to 5keV have been reached. Pronounced differences in the electron temperature profiles where found for co- and counter current drive (positive φ_{inj} leads to co-current drive), see Fig. 1. In the first case the profiles are peaked, displaying the driven electron-root feature [2] for small launching angles (for higher launching angles the beam becomes defocused leading to broader deposition profiles and smaller central temperatures). In the counter ECCD cases the profiles are very flat in the central region which is attributed to the strong decrease of the ι-profile due to the high central ECCD densities.

A scan of the toroidal lauching angle was performed to compare with the linear prediction (I_{inj}) based on a Maxwellian distribution with trapped particle effects included (in the very $lmfp$ limit for the realistic magnetic topology of W7-AS, so-called adjoint approach, see [3]). Results are shown in Fig. 2.

Analysis

Fig. 2 shows that the linear theory (I_{inj}) overestimates the ECCD efficiency for higher lauching angles, where its maximum is expected from theory. The deviation is more severe

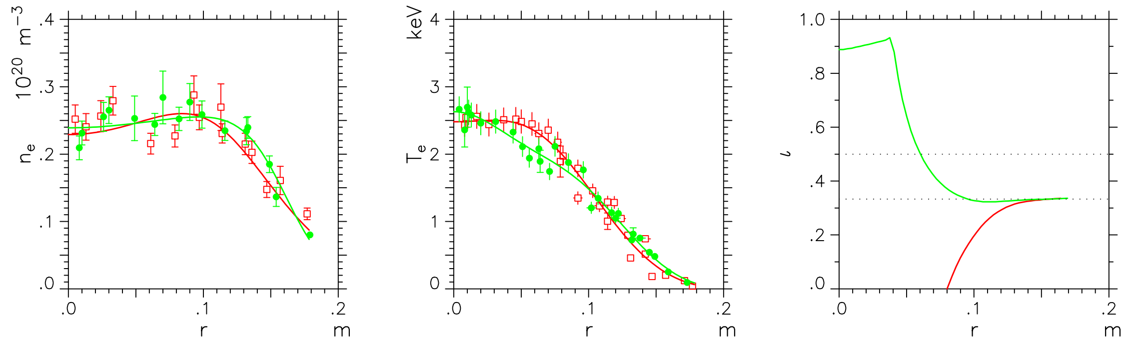

Figure 1: *1.2MW ECCD,shots 43040 (•, co) and 43061 (□, ctr.), with launching angles $\varphi_{inj} = \pm 20$, respectively. Profiles of electron density, temperature and estimated* ι*-profile.*

for co- than for the counter-current drive which shows reasonable agreement. This result is examined in different directions.

First, a major difference in co- and counter current drive is in the resulting ι-profiles (Fig. 1). Whereas for co-current drive the ι-values are increased towards the axis by ECCD, a linear analysis of the ι-change in the stationary phase of the counter current drive would suggest a ι=0-surface around the position where the temperature profiles flatten. Equilibrium considerations would exclude an $\iota = 0$-surface under the assumption of nested flux surfaces in this part because of the divergence of the Pfirsch-Schlüter currents at such a surface. Equilibrium calculations also show that ι-profiles with very low central values can only support negligible pressure gradients without generating large Shafranov shifts. On the other hand, the ECCD as well as the heating is coupled with a B-field resonance so that current and heating should be localized if flux surfaces do exist and ι-profiles crossing zero would be possible. The problem can be resolved by the assumption of an ergodic field for the inner part (where the profiles are flat) leading to a fast parallel transport for energy and current which results in a much broader deposition profile and flattened temperatures. In this case, the high power density would be reduced by the enhanced volume avoiding a breakdown of the linear and quasi-linear theory. However, the mismatch for the co-current drive remains.

Next, we checked the assumption of stationarity for the discharges of the co-current drive scenarios. Here, the high central temperatures lead to rather long skin times for the

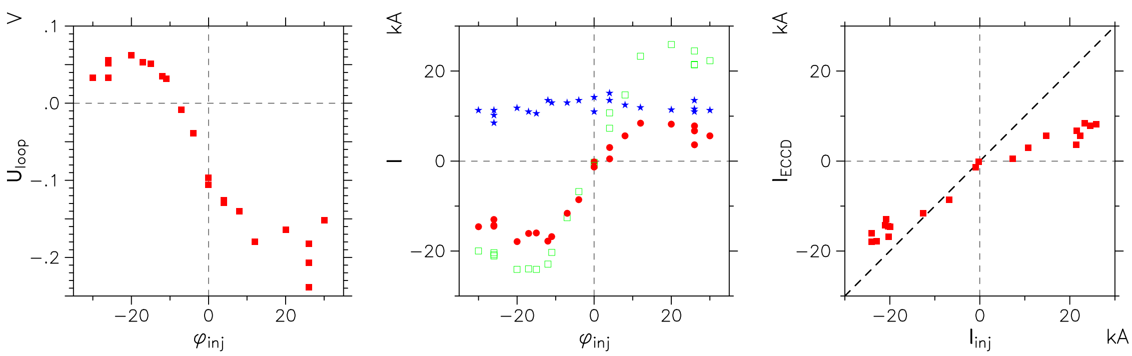

Figure 2: *1.2MW ECCD,shots 43023-62, scan of launching angle φ_{inj}: Loop voltages (left), bootstrap (⋆)- and ECCD (•)- current and I_{inj} (□) (middle), and experiment vs theory (right).*

current diffusion so that a part of I_{ECCD} could be masked by self-induced loop voltage which has to diffuse to the plasma boundary to be detected. Solving the current diffusion equation for stationary density and temperature profiles showed the long time-scales involved. However, keeping in mind that the plasma start-up is already done with current drive, we conclude that the discharges should be at least marginally stationary at the times where the current balance is made. Also, the time-traces of U_{loop} in the discharges show, that U_{loop} develops in the start-up phase and is stationary at the times of the current balance.

Another problem may be the current balance itself. In the case of counter current drive the main contributions are from the bootstrap current and the ECCD. A small portion of ohmic current is required to get a vanishing total plasma current. A situation which is quite comfortable. On the other hand, for co-current drive bootstrap current and ECCD have to be compensated by a strong ohmic current, so that the ECCD calculated from the current balance results from the difference of large numbers. Moreover, the neoclassical calculation of the bootstrap current is complicated by the appearence of a central electron-root, experimentally seen as an additional peaking of central electron temperature profiles. Nevertheless, since the current balance has been performed quite successfully for the cases without current drive, it seems reasonable to trust the analysis in the cases of co-current drive, too.

Keeping the above mentioned uncertainties in mind, we investigated the possibilities of kinetic reasons for a degradation of the ECCD efficiency. This was done by means of Fokker-Planck modelling of the heating around the axis by restricting the geometry to the flux tube of the magnetic axis [1]. In this approximation the problem is numerically tractable since bounce-averaging can be applied to reduce the dimensionality. Moreover, investigating the cases at higher launching angles (at maximum ECCD efficiency) is conservative since the non-linear degradation of the power absorption with respect to the quasi-linear treatment is in these cases less important (see M.F. Heyn et al., this conference). To reach a stationary state in the calculations, the strong heating as formulated by the traditional quasi-linear diffusion term (with the diffusion coefficient $Q_{\perp\perp}$ obtained from ray-tracing calculations [3]) is balanced by the energy loss of mainly suprathermal ripple-trapped electrons. In this stellarator-specific approach, the radial ∇B-drift of the ripple-trapped electrons broadens the "effective" power deposition profile in the velocity space [4] (see Fig. 3). Its influence on the ECCD-efficiency, however, is negligible. Moreover, the Fokker-Planck calculations show that the supra-thermal electrons generated by

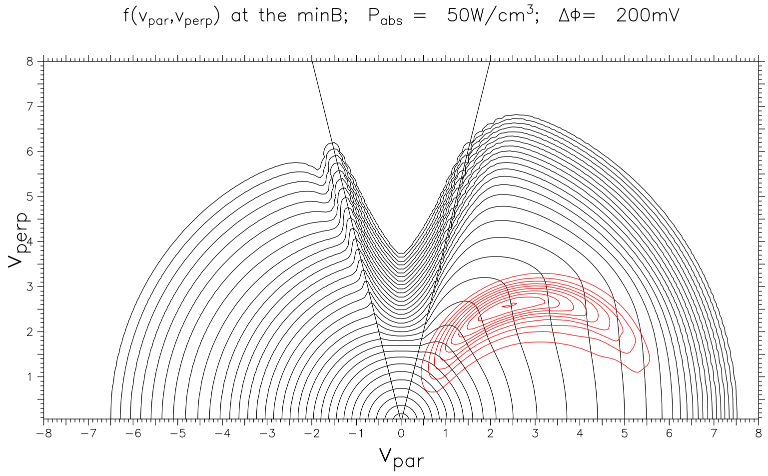

Figure 3: *Contour levels of distribution function at the minimum B-location resulting from Fokker-Planck modelling and contour levels of quasi-linear heating term. The distribution function is distorted by influence of the loss cone and the heating.*

the ECRH have only a negligible effect on the electric conductivity since the generated $v_{||}$-tails are too small. Additionally, if we go to high power levels, we see the formation of a quasi-linear "plateau" in the electron distribution function which, in contrast to the experimental results, slightly increases the ECCD efficiency.

To get a reduction of the ECCD efficiency with increasing power one has to introduce a strong momentum sink. We have modelled this by an isotropic power sink which can be interpreted as a simulation of an "anomalous" transport resulting from, for example, ergodicity due to the high central current densities being related to large shear and ι-values with the possibility of island overlapping.

A closer look at the electron distribution function in Fig. 3 leads to another approach. By using the convective ∇B-drift loss model, strongly positive gradients with respect to $v_{||}$ close to the loss-cone boundary are found in the electron distribution function. They represent free energy and may drive the electron distribution function unstable. Due to the fast growth rates of these kinetic instabilities, they can effectively reduce the underlying free energy changing the electron distribution function with the result of a degradation in the ECCD efficiency. The calculated electron distribution functions are currently investigated with respect to kinetic instabilities.

Discussion and Conclusions

High power ECCD experiments were performed to investigate the validity of the linear and quasi-linear theory. Large EC-driven currents as derived from the current balance of up to $\pm 20kA$ have been obtained, and reasonable agreement with linear theory is derived for the counter current drive, whereas for co-current drive the ECCD efficiency seems to be overestimated. The difference in agreement in co- and counter current drive is understood by the assumption of degraded confinement in the plasma center for counter current drive due to the "formal" appearence of an ι=0-surface leading to a reduced power density preventing the breakdown of linear theory. The degradation of the ECCD efficiency in the co-current drive scenario is not easily understood since stationarity and validity of the current balance seem to be reasonable. Fokker-Planck modelling with a pure convective ∇B-drift loss model was also not sufficient, but a strong momentum sink had to be introduced to reproduce a degradation of the ECCD efficiency with increasing power. Currently the possibility is investigated whether the strong positive gradients with respect to $v_{||}$ in the electron distribution function derived from the Fokker-Planck calculations may drive kinetic instabilities providing such a momentum sink. Experiments to investigate the dependence of the ECCD-efficiency on electron density and power density should be initiated. Also experiments in which the current drive is switched from co- to counter-launching could give insight into the dynamics of the current diffusion.

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