ECRH and ECCD Experiments in an Extended Power Range with 70 and 140 GHz at the W7-AS Stellarator

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An overview on physics studies on ECRH and ECCD in an extended parameter range at W7-AS is presented. Experiments were performed with an upgraded ECRH power of up to 1.5 MW at 140 GHz and 0.4 MW at 70 GHz. Both systems have a flexible optical launching system for on/off axis heating and current drive. The power can be modulated with frequencies up to 10 kHz for perturbative studies of heat transport, power deposition and current drive. The 140 GHz system operates in 2nd harmonic X-mode (X2) launch at 2.5 T. Electron temperatures of up to 5.7 keV, which can only be explained by the beneficial effect of positive radial electric fields (‘electron root’) [1], were measured with 1.3 MW heating power at densities of 2 10^{19} m^{-3}. This electric field is generated by ECRH driven particle losses as experimentally confirmed by the threshold behaviour and the response to heating inside and outside the loss cone. At the highest power densities of about 50 MW/m^{-3} burst-like instabilities are observed from ECE, which occur on a much faster time scale than the collisional one and are attributed to wave instabilities.

The accessible plasma density with X2 heating is limited by the cut-off condition (<1.25 10^{20} m^{-3}). This restriction is removed with mode conversion heating, where an ordinary mode is converted to an extraordinary and finally to Electron Bernstein Modes (O-X-B process) [2]. Heating via the O-X-B process at densities far above the X2 cut-off was successfully applied for the first time at W7-AS, a thorough analysis of the experiments is presented. The theoretically predicted parameter dependence on the density gradient, launch angle, and magnetic induction was investigated experimentally and good agreement with theory was found. Localized power deposition of the electron Bernstein waves was measured as a function of the magnetic induction as shown in Fig. 1.

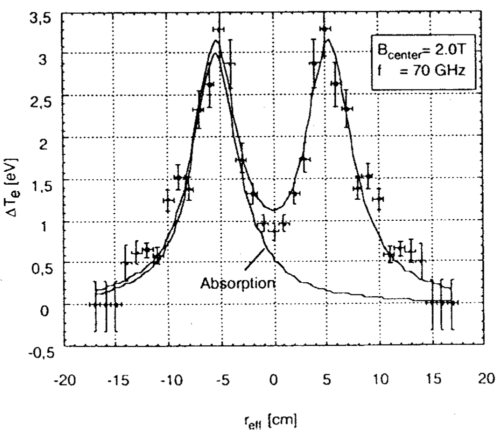

Fig. 1. Localized absorption of Electron-Bernstein waves in experiments with mode conversion heating. The deposition profile is obtained from SX-diagnostics (switch-off technique).

New ECCD experiments were performed at high input power (1.2 MW). The EC driven current can be measured with a high accuracy (±100 A) because it is not masked by a large inductively driven current as in tokamaks. A toroidal launch angle scan was performed at a density of 2.5 10^{19} m^{-3} with inductive compensation of the EC driven current (I_p=0) to maintain net current free conditions with $I_{ind} + I_{boot} + I_{ECCD} = 0$ (I_{ind} is the inductive component, I_{boot} and I_{ECCD} are the bootstrap and the EC-driven components, respectively). The microwaves were injected from low field side in X2 mode polarization. During the scan the toroidal magnetic field was adjusted to keep the (Doppler shifted) deposition profile close to the plasma axis ($\Delta B / B \cong 10\%$, for $|\varphi_{inj}| = 30^o$). Under these conditions, linear ray tracing predicts a peaked deposition profile with power densities of the order off 50 MW/m^{-3}. The required inductive loop voltage is shown in Fig. 2 as a function of the launch angle ($\varphi_{inj} = 0^o$ corresponds to perpendicular injection, $I_{ind} = - I_{boot}$), together with the linear ECCD-efficiency from ray-tracing [3] using the measured density and temperature profiles. The dependence on the toroidal angle of injection is accurately reproduced. To obtain quantitative agreement, a plasma resistivity of $R \approx 4\ \mu\Omega$ has to be assumed, which is close to the neoclassical Spitzer value $4 \leq R_{neo}\ [\mu\Omega] \leq 6$ predicted for $Z_{eff} = 2$. No strong discrepancy with linear theory is therefore observed (if trapped particle effects are included), even at these extremely high power densities. The maximum efficiency $\eta_{ECCD} \cong 30$ A/kW corresponds to a normalized efficiency $\gamma_{ECCD} = n_e I_{ECCD} R/P_{ECRH} \cong 0.015\ 10^{20}\ A/Wm^2$. One has to notice that due to the low-field-side injection, the EC-waves tend to interact and be absorbed by electrons from the bulk of the distribution function and collisions are sufficient to suppress a strong deformation of the Maxwellian distribution function. A different situation would appear if the power could be deposited to tail electrons. In this case a higher ECCD-efficiency is expected and quasi-linear effects become of importance even at considerably lower power densities.

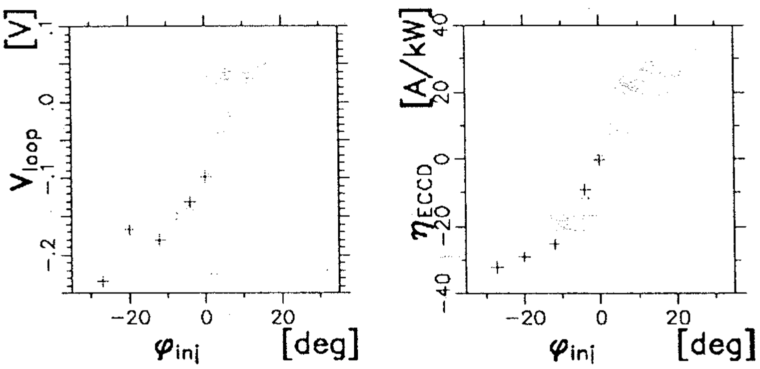

Fig. 2. Left: Loop voltage vs. toroidal angle of injection in net current free discharges, $V_{loop} = -(I_{boot} + I_{ECCD}) / R_\Omega$. $\varphi_{inj} = 0^o$ corresponds to perpendicular injection. Right: Theoretically predicted current drive efficiency (linear theory including trapped particle effects).

The different current contributions flow at different radial positions, i.e. the bootstrap current is localized in the pressure gradient region whereas the inductive current follows the plasma conductivity profile and the ECCD is localized around the resonance. Thus the radial profile of the rotational transform can be strongly modified by ECCD. Experiments were performed with negative rotational transform in the plasma centre, i.e. $\iota = 0$ inside the plasma and, for co-CD, central rotational transform well above $\iota > 0.5$. In the latter case strong ECCD driven m=2 tearing mode activity is observed.

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[2] H.P. Laqua et al., Phys. Rev. Lett. **78**, 3467 (1997)
[3] Gasparino, U. et al., Theory of Fusion Plasmas, Varenna, (1990) 195