ECRH AND ECCD EXPERIMENTS IN AN EXTENDED POWER RANGE AT THE W7-AS STELLARATOR

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Abstract

An overview on physics studies on Electron Cyclotron Resonance Heating (ECRH) and ECCurrent Drive (ECCD) in an extended parameter range at W7-AS is presented. Experiments were performed with an upgraded ECRH power of up to 1.3 MW at 140 GHz. Electron temperatures of up to 5.7 keV were measured, which can only be explained by the beneficial effect of positive radial electric fields (‘electron root’). The experiments confirm, that the electric field is generated by ECRH driven particle losses in the specific stellarator magnetic field. ECCD experiments were performed at high input power (1.3 MW) resulting in EC-driven currents of up to 20 kA. The direction of the EC-driven current was varied in co- and counter-direction with respect to the bootstrap current in discharges with zero net-current. Three current contributions, i.e. the EC-driven current, the bootstrap current and the inductively driven current are calculated independently and modify the internal profile of the rotational transform significantly. A comparison with quasi-linear theory shows significant deviation in the co-current drive case, which may be attributed to strong MHD activity and/or violation of the quasilinear assumptions due to the high power density.

1. INTRODUCTION

Investigations on ECRH and ECCD at W7-AS [1] were continued with an upgraded ECRH heating power of up to 1.3 MW at 140 GHz, which corresponds to a resonant magnetic field of 2.5 T at 2nd harmonic X-mode (X2). The heating experiments cover the full accessible density range up to the cut-off density of 1.25×10^{20} m^{-3}, whereas we have restricted the ECCD experiments to densities around 0.25×10^{20} m^{-3}. The microwaves are absorbed in a narrow region around the resonant magnetic field and thus the power density increases up to 50 MW/ m^{-3} in a flux surface average, which is far beyond the limits, were linear theory holds and nonlinear phenomena are expected to occur. At high power density, the electron distribution function flattens at the resonance and the absorption is shifted towards higher energies thus generating a suprathermal tail [1,2]. This quasilinear effect increases the ECCD-efficiency with respect to linear theory. Nonlinear wave-particle interaction, which is maximum for ripple trapped electrons with small parallel velocities is, however, expected to reduce the ECCD efficiency. Furthermore, a strong deformation of the electron distribution function may be unstable thus affecting the driven current.

2. CENTRAL CONFINEMENT WITH STRONG ECRH

Experiments with strong X2-mode heating were performed in a wide density range at constant input power of 1.3 MW in low field side launch in the equatorial plane. Radial profiles of T_e and n_e are shown in Fig. 1. The central electron temperatures range from 5.7 keV at 1.7×10^{19} m^{-3} to 3 keV at 7.5×10^{19} m^{-3}. A pronounced steepening of the temperature gradients is seen in the centre of the plasma at densities below 4×10^{20} m^{-3}. The stationary transport analysis of these discharges results in a central (r/a < 0.3) electron heat diffusivity, which is well below the neoclassical heat diffusivity, once electric fields are neglected. Strong positive radial electric fields up to 50 kV/m were measured in the plasma centre, which lead to good agreement with neoclassical theory including electric fields ('electron root solution'). It is worth noting, that the ions are energetically decoupled from the electrons under these conditions and the energy balance is dominated by the electrons.

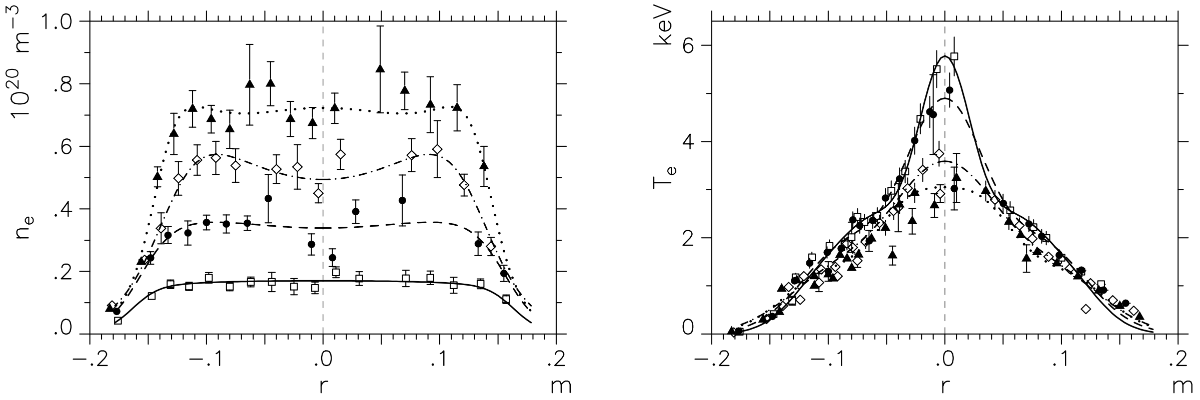

Fig. 1. Radial profiles of the electron density (left) and temperature (right) with 1.2 MW ECRH.

The appearance of the electric fields - and the corresponding steep temperature gradients- shows a threshold behaviour at a density around 0.2 - 0.4 $\times 10^{20}$ m^{-3}, a similar behaviour was measured during a power scan from 0.2 MW to 1.3 MW input power at constant density of 0.2 $\times 10^{20}$ m^{-3}, where the steepening occurred between 0.2 and 0.4 MW. The discharge could be placed at the threshold by careful adjustment of the heating power density while tuning the deposition region. The central electron temperature then is jumping iteratively between two states of low (say 4 keV) and high (5 keV) temperature during one discharge with some hysteresis between rise and fall-time constants. The experiments are explained by a substantial loss of fast trapped particles driven by ECRH itself, which in turn generates a positive electric field with its beneficial effect on the bulk electrons [3,4]. This picture is consistent with the results of switching experiments, where the central confinement is lost on a fast timescale (< 0.3 ms), whereas the remaining profile relaxes on the diffusion timescale. Also these switching experiments display a threshold nature while switching from 1.2 to 0.8 to 0.4 MW.

3. ELECTRON CYCLOTRON CURRENT DRIVE

A toroidal launch angle scan was performed at 1.2 MW launched power and a density of 2.5 $\times 10^{19}$ m^{-3} with inductive compensation of the EC driven current 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, the polarization was adjusted according to the given launch angle from linear to elliptical polarization to provide optimum coupling of the microwaves. 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, ray-tracing calculations predict a peaked deposition profile with flux surface averaged power densities of up to 50 MW/m^3. The required inductive loop voltage for current compensation is shown in Fig. 2 (left) as a function of the launch angle φ_{inj} ($\varphi_{inj} = 0^o$ corresponds to perpendicular injection, $I_{ECCD} = 0$). For a quantitative comparison of the measured data with theory we assume a linear superposition of the three current contributions, which is justified, because the suprathermal electrons generated by ECRH have only a negligible effect on the electric conductivity as confirmed by Fokker-Planck calculations [5]. The bootstrap current is calculated by the DKES code taking into account the ambipolar radial electric field, and the inductive current is calculated assuming neoclassical resistivity (effective charge Z_{eff} = 3-6), the calculations are performed for each individual discharge using the measured profiles of n_e and T_e. Then the EC driven current from the current balance $I_{ECCD} = -I_{ind} - I_{boot}$ is plotted in Fig. 2 and compared with the linear theoretical ECCD current, I_{inj}. The maximum linear ECCD-efficiency from ray-tracing (based on the adjoint approach with trapped particles [6] included), $\eta_{ECCD} \cong 20$ A/kW corresponds to a normalized efficiency $\gamma_{ECRH} = n_e\, I_{ECCD}\, R\, /\, P_{ECRH} \cong 0.01 \times 10^{20}$ A/Wm^2.

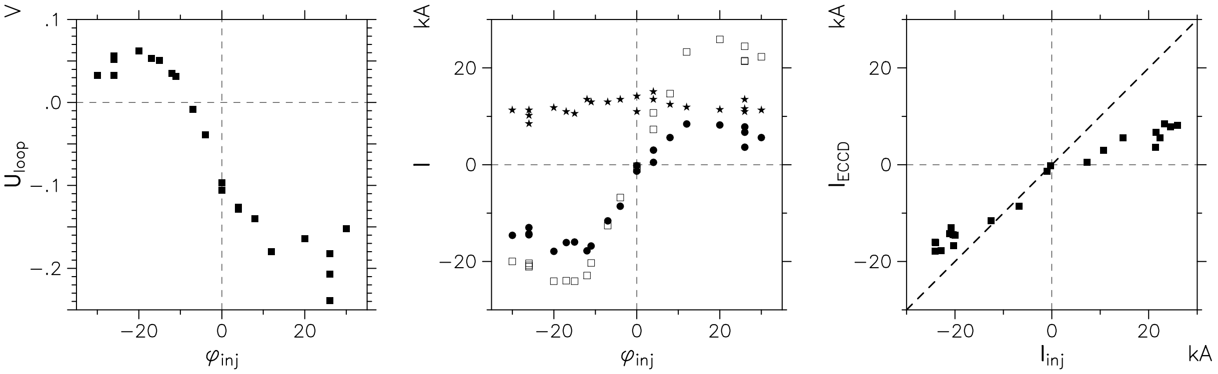

Fig. 2. Left: Loop voltage vs. toroidal angle of injection in net current free discharges, U_{loop} = -(I_{boot} + I_{ECCD}) / R. Perpendicular injection corresponds to $\varphi_{inj} = 0^o$. Centre: Theoretical (open squares) and data from current balance of the EC-driven current (dots) together with the bootstrap current (stars) as a function of the launch angle. Right: EC-driven current from current balance versus linear prediction.

As seen from Fig. 2 (right), where the ‘experimental’ I_{ECCD} is plotted versus theory, good agreement with linear theory is observed even at these extremely high power densities except for launch angles in co-direction. This may be a hint for a degradation of the CD-efficiency at high power density. The calculations of both the inductive and the bootstrap current are very conservative and are expected to be more reliable than the linear ECCD calculations, where the assumptions of the linear approach are likely to be violated. Non-linear effects in the wave-particle interaction in an inhomogeneous magnetic field are important especially at moderate launch angles. Thus the quasi-linear theory, which holds in a homogenous magnetic field must be reformulated. In addition the wave absorption increases the perpendicular energy and pushes electrons into the loss cone. In the bounce-averaged Fokker-Planck calculation the strong heating as formulated by the traditional quasi-linear diffusion term is balanced by the energy loss of mainly suprathermal ripple-trapped electrons. The radial ∇B-drift of suprathermal ripple-trapped electrons broadens the power deposition profile [3] but has no influence on the ECCD profile. In the electron distribution function, however, positive gradients with respect to $v_{||}$ close to the loss-cone boundary are found, which represent free energy and may drive the distribution function unstable. The fast growth rate of such kinetic instabilities affects the distribution function and can reduce the CD-efficiency, which would again require a reformulation of Fokker-Planck modelling.

In discharges with strong co-CD, MHD-activity is observed, which is absent in the counter-CD cases. This is explained by the strong change of the radial profile of the rotational transform while scanning from co- to counter-CD, because the different current contributions flow at different radial positions. The bootstrap current is localized in the pressure gradient region whereas the inductive current follows the plasma conductivity profile and the EC-driven current is localized around the resonance. Figure 3 shows radial profiles of n_e and T_e together with the rotational transform for co- and counter CD.

For co-CD the temperature profiles remain peaked and the ι −profile crosses the $\iota = 1/3$ and $\iota = 1/2$ surfaces with strong shear. The observed MHD-modes are the corresponding m=3 and m=2 modes, which may influence the current distribution. The modes are located around the rational ι values as measured by ECE, soft-X and Mirnov diagnostics. In the opposite case of counter-CD the $\iota = 0$ surface appears in the plasma centre and the temperature profile is flat within this surface indicating bad or no confinement within this surface. In consequence the EC-driven current within the $\iota = 0$ surface may be distributed over a wider volume than calculated by ray tracing, leading to a reduced power density, a lower deviation from a Maxwellian distribution function and thus to a better agreement with linear CD-theory.

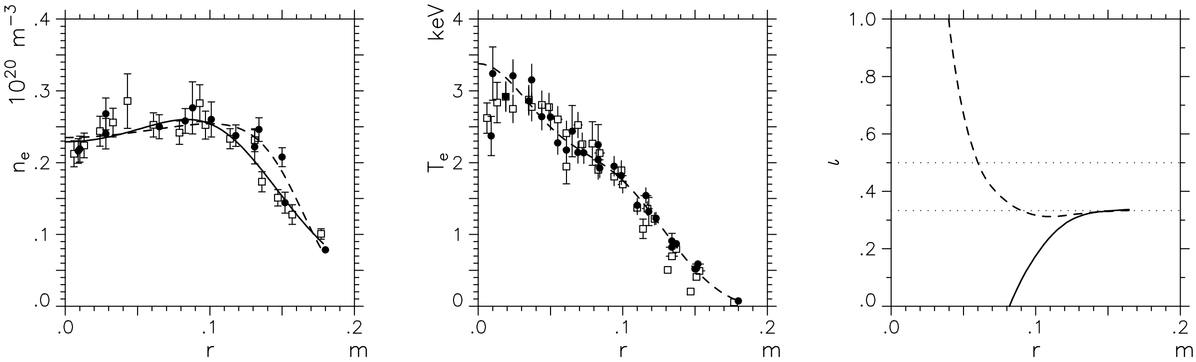

Fig. 3. Radial profiles of the electron density n_e (left), electron temperature T_e (centre) and rotational transform ι (right) for co- (dashed line) and counter-CD (solid line) at zero net-current, φ_{inj} = + and - 12^o, respectively.

4. CONCLUSIONS

Experiments on ECRH and ECCD were performed at W7-AS with enhanced heating power, which is well beyond the previous frame of investigations. New physics arrives in the experiments and drives theory into the interpretation of strong kinetic effects. The central confinement of ECR-heated discharges is strongly influenced by ECRH specific features. Positive radial electric fields driven by fast electron losses in the plasma centre (‘electron root’) provide significantly enhanced electron confinement resulting in peak temperatures of 5.7 keV.

Net current free discharges with up to 20 kA of highly localized EC-driven currents in co- and counter-direction to the bootstrap current were investigated and compared with linear predictions. The experiments indicate under some conditions a deviation from linear ECCD theory, which asks for advanced kinetic modelling.

The radial profile of the rotatational transform was tailored by strong ECCD in a wide range from tokamak-like profiles, which exhibit rational resonances of ι with related MHD-activity, to inverse profiles, where ι = 0 with bad or no confinement appears in the inner plasma region.

REFERENCES

[1] ERCKMANN, V. and GASPARINO, U., Electron Cyclotron Resonance Heating and Current Drive in toroidal Fusion Plasmas, Plasma Phys. Control. Fusion **36** (1994) p. 1869.

[2] ROMÉ, M., ERCKMANN, V., GASPARINO, U., HARTFUSS, H.J., KÜHNER, G., MAASSBERG, H., MARUSHCHENKO, N., Kinetic modelling of the ECRH power deposition in W7-AS, Plasma Phys. Control. Fusion **39** (1997) 117-158.

[3] MURAKAMI, S., GASPARINO, U., IDEI, H., KUBO, S., MAASSBERG, H., MARUSHCHENKO, N., NAKAJIMA, N., ROMÉ, M., OKAMOTO, M., 5D Simulation study of suprathermal electron transport in non-axissysmmetric plasmas, Paper IAEA-CN-69/TH2/1 (R) THP1/1, this conference.

[4] MAASSBERG, H., BEIDLER, C.D., DYABILIN, K.S., GASPARINO, U., MURAKAMI, S., W7-AS TEAM, The neoclassical ‘electron root’ feature in the W7-AS stellarator, submitted for publication to: Plasma Phys. Control. Fusion.

[5] MARUSHCHENKO, N., GASPARINO, U., MAASSBERG, H., ROMÉ, M., Bounce averaged Fokker-Planck code for the description of ECRH in a periodic magnetic field, Comput. Phys. Comm. **103**, (1997) 145-156.

[6] ROMÉ, M., ERCKMANN, V., GASPARINO, U., and KARULIN, N., Electron cyclotron resonance heating and current drive in the W7-X stellarator, Plasma Phys. Control. Fusion **40** (1998) 511-530.