

Equilibrium calculations for the W7-AS stellarator with large internal current densities due to ECCD

J.Geiger¹, H. Maassberg¹, N.B. Marushchenko¹, M. Romé², A. Weller¹

¹Max-Planck-Inst. f. Plasmaphysik, Euratom Ass., 17491 Greifswald, Germany

²I.N.F.M., I.N.F.N., Dip. di Fisica, Univ. degli Studi di Milano, 20133 Milano, Italy

Introduction

Electron cyclotron resonance heating (ECRH) was one of the major heating systems of the W7-AS stellarator. Additionally, it has been considered for current drive scenarios for W7-X to control the edge rotational transform t_a in case that a bootstrap current or an NBI-driven current arises preventing proper island divertor operation. The experiments performed to investigate the prospects of ECRH current drive (ECCD) are described in [1]. A basic result of [1] was that the current balance consisting of ECCD-current, bootstrap current and ohmic current gave good agreement with the theoretical predictions in case of counter-ECCD (which lowers t) whereas for co-ECCD conditions (which increases t) the predicted currents were too large when compared with the experiments, especially for low density discharges. Here, we investigate these discharges from the vantage point of MHD-equilibrium and stability since some of the resulting current densities are extreme due to the localized ECRH. The equilibrium calculations in this work were performed with the VMEC-code².

Co-current drive

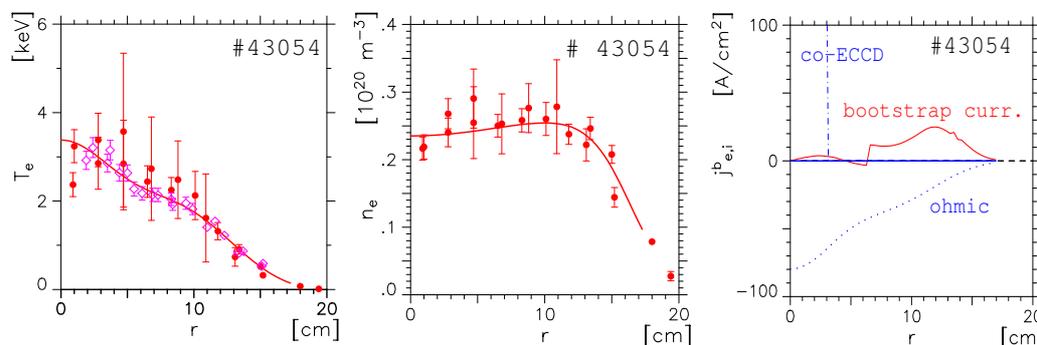


Figure 1: Co-ECCD: Profiles of electron temperature, density and of current densities as derived from transport analysis. ECCD-profile has been assumed to be of rectangular shape.

Fig. 1 shows the profiles of electron temperature, density and of the current densities as derived from a transport analysis. Ion temperatures are in the range of 200eV and therefore negligible for these high- T_e conditions. The ohmic current was calculated from the neoclassical resistivity and the measured loop voltage and the bootstrap current resulted from a neoclassical transport analysis which showed an e-root feature at the center suppressing the bootstrap current where the radial electric fields are sufficiently large. Since the current balance shows good agreement in discharges without ECCD these contributions are considered reliable. For simplicity, the ECCD-current of 9.7kA resulting from the current balance was assumed to be equally distributed within 3cm around the magnetic axis (modelled by a rectangular profile). An estimation of the t -profile from the total current density using the cylindrical formula in Fig. 2 shows an increase of the central t beyond values of 1 due to the strong ECCD current

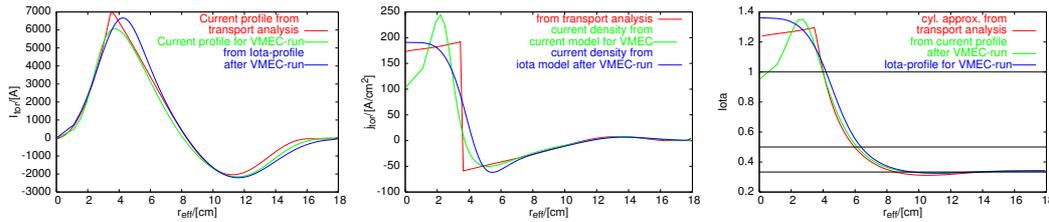


Figure 2: Co-ECCD: Comparison of current, current density and t -profiles from transport analysis (t -correction in cylindrical approximation) and equilibrium calculations with either the current or the t -profile as input.

density. At larger values of r_{eff} , t falls to reach the boundary value of about 0.34 with a slight excursion below the resonance $t = 1/3$. The analytical estimate is compared with two equilibrium calculation in which (1) the profile for the toroidal current was prescribed being chosen to model the one from the transport analysis and (2) with a given t -profile modelling the cylindrical estimation. The calculations recover either the current profile or the t -profile of each other very well. In the experiments the low order resonances in the t -profile were confirmed by the observation of prominent $(m,n)=(2,1)$ tearing modes in Mirnov- and ECE-temperature measurements. Also, $(3,1)$ tearing modes were observed in SX-ray and ECE measurements supporting the assumption that the t -profile contains a local minimum below $t = 1/3$. A subsequent analysis with a Δ' -code³ adjusted to include an external rotational transform is difficult to interpret. The profiles from the transport analysis are stable with respect to the $(2,1)$ -mode but unstable to the two modes with $(m,n)=(3,1)$ with estimated island widths of 3-4 cm. The model current profile for the VMEC calculation is only unstable with respect to the outer $(3,1)$ mode, whereas the case with the prescribed t -profile is unstable to all three modes. In an additional case study, varying the t -profiles, a similar picture arises. Most cases show instability of all modes but sometimes the $(2,1)$ or the inner $(3,1)$ mode is stable. Presently, the numerical result is not fully understood. The conjecture is that the small shear and the small current density gradients around the resonance $t = 1/3$ which extends over almost half of the minor radius is responsible for these different results which must, therefore, be taken with care. Additionally, Fig. 3 shows the change of the flux surface shape due to the large current densities around the axis resulting in more oblate flux surfaces for co-ECCD and more elongated ones for ctr-ECCD. This was already observed in comparisons of VMEC-calculations and SX-ray measurements for cases with net-toroidal currents⁴.

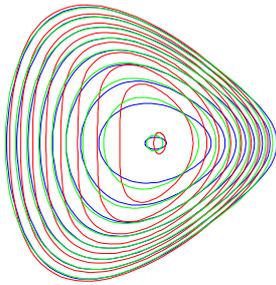


Figure 3: Flux surfaces from VMEC-calculations with co-ECCD (blue), ctr-ECCD (green) and for reference without ECCD (red).

measurements for cases with net-toroidal currents⁴.

Counter-current drive

In these discharges a rather small loop voltage was observed so that the main part of the compensation of the bootstrap current was taken over by the counter-ECCD current. The resulting current densities from the transport analysis are rather exceptional in the sense that the cylindrical approximation for the resulting t -change leads to the appearance of $t = 0$ at around half of the plasma radius and to an inner region with negative t . The experimental profiles in

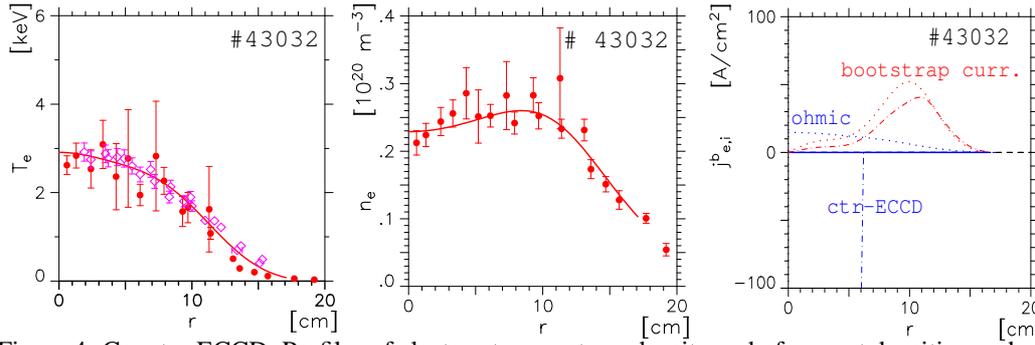


Figure 4: Counter-ECCD: Profiles of electron temperature, density and of current densities as derived from transport analysis. ECCD-profile assumed.

Fig. 4 show a flattening of the electron temperature profiles which contrasts to the expected very local on-axis heating, revealing bad confinement in this inner region. This flattening is not well represented in the shown T_e -fit. Based on the flat T_e -profiles, in a first step the ctr-ECCD current was distributed over a wider volume than in the co-ECCD case (6.5cm vs 3cm). But even this leads to central t -values around -0.5 in the cylindrical approximation. Equilibrium

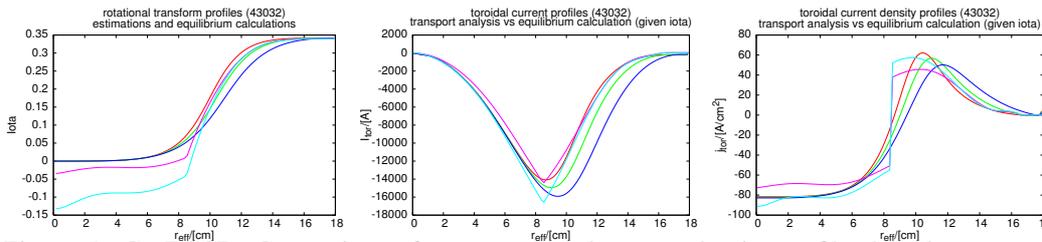


Figure 5: Ctr-ECCD: Comparison of t -, current and current density profiles based on transport analysis (t -correction in cyl.approx.), on 3 models and the corresponding equilibrium calculations based with the t -profile as input. calculations based on these current profiles pose no problem to VMEC as no division by t is required. However, the iteration procedure stagnates since the existence of an $t = 0$ surface together with small pressure gradients require the code to reduce the iteration time step. The code thus prevents the formation of an outer x-point at the $t = 0$ surface since its numerics is based on nested flux surfaces. Therefore, input modus was switched from the current to the t -profile. The model t -profiles start in the center from $t = 0$ and rise towards the boundary, roughly where the T_e -gradients start to appear. Such profiles rest on the idea that very low t -values will prevent the buildup of gradients and a formation of negative t -regions with nested flux surfaces. Fig. 5 shows the 3 input profiles for VMEC runs and the analytic t -corrections where we distributed the ECCD-current of up to 24kA on an enlarged range of 8.5cm. The conditions are rather similar to the ones in tokamaks with current holes⁵. With the t -input profiles it is possible to reproduce the current density profiles from the transport analysis rather well. The reason for the bad confinement becomes obvious when looking at the electron drift orbits in the resulting equilibrium magnetic field as shown in Fig. 6. Shown are orbits of co- and counter-passing electrons with two times the thermal energy (6keV, pitch angle = 45°). They are basically drifting vertically through the very low t -region before they are able to close in regions with higher t thus giving the picture of a "convection cell" equally distributing energy

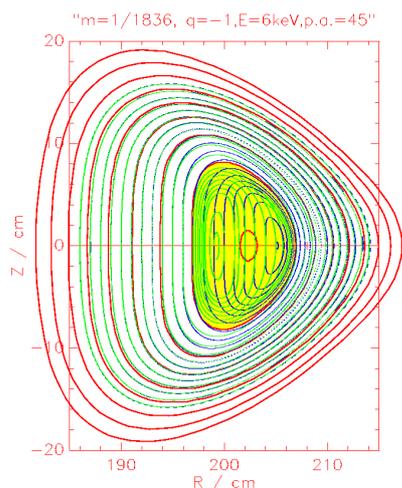


Figure 6: Orbits of co (green) and counter (blue) going electrons in a VMEC-equilibrium (flux surfaces in red) with centrally reduced ι -values. The range with $\iota \leq 0.014(r_{eff} \approx 6.5\text{cm})$ is marked in yellow.

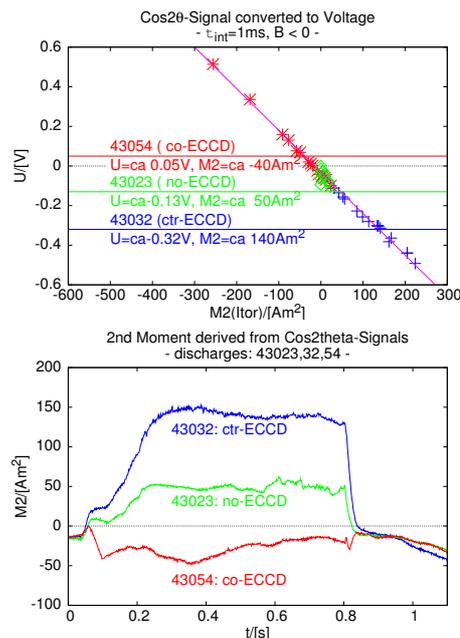


Figure 7: Upper: relation of 2nd radial moment $M2$ of the toroidal current density to signals in the $Cos2\theta$ -coil system calculated with the DIAGNO package. Lower: time trace of the $M2$ as derived from $Cos2\theta$ -raw signals and dependence, given in upper plot.

and current in this inner part. Confirmation for the assumed current profiles comes from a comparison of measurements with the so-called $Cos2\theta$ -coil system (4 segmented Rogowski coils in a ”+-+”-wiring) with equilibrium calculations using VMEC and the DIAGNO-package. The signal is most sensitive to the radial distribution of the current density as shown in Fig. 7, i.e. the 2nd moment ($\sim \int j_{tor} r^2 r dr$). The experimentally derived one compares rather well with the ones resulting from the equilibrium calculations.

Conclusions

Although highly localized ECCD generates extreme current profiles in the W7-AS stellarator, the equilibrium analysis leads to a consistent picture. For co-ECCD the low order rationals are identified by prominent tearing modes, although the presently performed Δ' -analysis shows some peculiarities. In the counter-ECCD case the electron drift-orbits in the presence of a central region of very low ι explain very well the flat T_e -profiles observed and the broad ECCD current distributions. Moreover, a qualitative confirmation for the radial distribution of the toroidal current can be obtained from magnetic measurements.

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