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ECCD and Bootstrap Current Profiles in Advanced Scenario Plasmas in TCV

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Introduction

The electron cyclotron wave (ECW) system is the only auxiliary plasma heating system on TCV: It provides both electron cyclotron heating (ECH) and current drive (ECCD). Starting with an inductively-driven, constant, plasma current, either the loop voltage is set to zero, or better yet, the external inductive electric field is set to zero by a feedback system just after ECCD is started. The ECCD is in the same direction as the existing plasma current (CO-CD). In this way, over the past few years, TCV has demonstrated that *1)* it is possible to drive the entire plasma current for ~2s by ECCD and the accompanying bootstrap current (~10-20%), *2)* when too much power is deposited centrally the plasma is disruptively MHD unstable, *3)* the normalized local current drive efficiency $\eta_T = IR_0n_e/T_e/P$ decreases rapidly as power is deposited at larger normalized radius ρ, consistent with particle trapping[1], and *4)* balancing points 2 and 3 leads to a maximum driven current in TCV of 210kA using all six 82.6GHz (2^{nd} harmonic X-mode: X2), 2s, 0.5MW gyrotrons of the ECW system[2]. In addition, by using two pairs of gyrotrons switched on one pair after the other, a 2.8s fully ECCD driven plasma of slightly more than 100kA has been demonstrated[3]. This has now been extended to 4s. This is the maximum possible pulse length in TCV and is determined by the ECW system.

Here we make a preliminary report on the extension of these results to steady-state fully ECCD driven advanced scenarios with ~80% bootstrap fraction by the use of *off-axis only* ECCD to create negative central shear (reversed shear).

General features of plasmas fully sustained by off-axis ECCD

The full plasma current has been driven non-inductively for the first time in TCV using 0.9MW of *off-axis* ECCD *only* from two of the gyrotrons in the system. None of the millimeter wave power is deposited near the center of the plasma. The presence of fast electrons at the plasma center and across the entire plasma cross-section is evidenced[4] by a hard X-ray camera on loan from CEA-Cadarache. Spatial (radial) diffusion of RF generated supra-thermal electrons away from the deposition region can supply current carrying fast electrons on-axis. As it also reduces the quasi-linear effects of RF diffusion, it can remove the order of magnitude discrepancy between the measured I_{CD} (45kA) and that calculated by the CQL3D Fokker-Planck code when radial diffusion is not included (460kA). (The power densities in TCV are well above those required for strong quasi-linear enhancement of the driven current[5].) Off-axis power deposition produces off-axis temperature and density gradients, favoring generation of bootstrap (BS) current. The addition of the ECCD and BS current profiles is peaked off-axis and the resulting safety factor profile exhibits good confinement[6].

Driven current profiles

In steady state, the total I_{CD} is given by the measured I_p minus the bootstrap current I_{BS}; which is calculated using the electron density and temperature profiles measured each 50ms by Thomson scattering. The externally applied electric field is kept zero by feedback. Internally generated electric fields are assumed to be zero if the plasma configuration is stable but, may play a role during transients. Cold plasma ray-tracing, performed using TORAY-GA, provides input for Fokker-Planck absorption and current drive calculations, using CQL3D. It has been shown recently with this code that radial diffusion play a much more important role in determining the current drive efficiency in TCV than, for example, in DIII-D[7]. The code provides two models for diffusion (and advection), with different parallel velocity dependencies; corresponding, approximately, to electrostatic (constant in $v_{//}$) and electromagnetic (~ $v_{//}$) anomalous radial diffusion. The radial profile of the diffusion coefficient increases towards the plasma edge in the model. A single fit parameter is then adjusted until the total driven current matches the measured value. (The advection term is adjusted to maintain the measured density profile. It is proportional to the diffusion coefficient). In the region of 6-D phase space where the power is deposited, the diffusion coefficients for both models match within approximately a factor of two (3-6m^2/s). The effect of diffusion is twofold. First, the current drive efficiency predicted for the high power densities of TCV is drastically reduced to values still larger than the linear result, and second, the I_{CD} is spread to the center of the plasma, although no power is directly deposited there. This is seen in figure 1a-d.

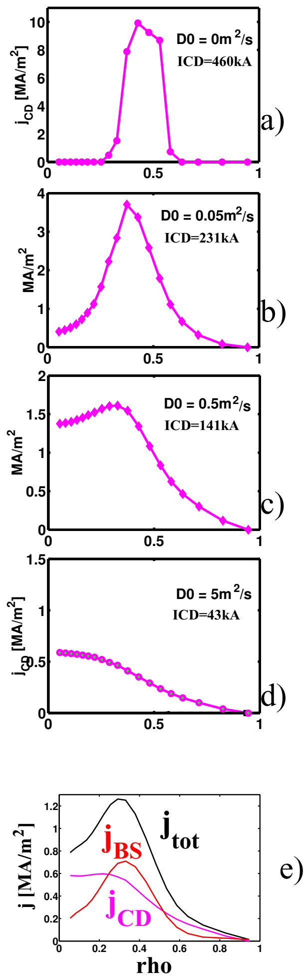

Figure 1 The CQL3D ECCD current profile broadens and the total driven current is reduced as radial diffusion is increased (a-d). The total current density profile (e) is a combination of the lower curve (d) and the bootstrap current calculated from the density and temperature profiles (Fig. 3)

The deposition location of the ECCD plays a crucial role in the evolution of the discharge. It determines the amount of ECCD driven current and the gradients that lead to the bootstrap current generation. The ratio of the two contributions to the total current will vary with the CO-CD deposition location. When far enough off-axis, the total current profile is very flat to slightly hollow as the off-axis peaked j_{BS} is added to the flattened j_{CD} profile. When counter-CD is added to this configuration inside of the CO-CD deposition location, j_{tot} becomes clearly hollow (Fig. 1e). The resulting current profile and the measured pressure profiles are used in CHEASE to reconstruct the q-profile (Fig. 2). The q-profile calculated by the standard TCV reconstruction code LIUQE, using external magnetic data and low order polynomials, is shown for comparison. A clear reversed shear profile is found by CHEASE.

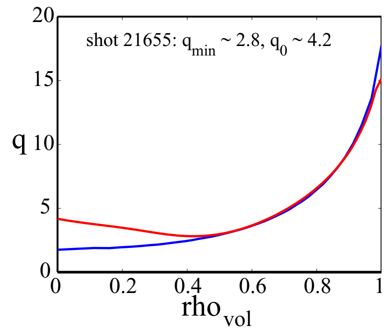

Figure 2. The reversed shear q-profile calculated by CHEASE using the current profiles of figure 1e (red curve) is compared with the "standard" profile found by the LIUQE reconstruction code (blue curve).

eITB creation and driven current

Rebut-Lallia-Watkins (RLW) global energy scaling describes most TCV plasmas well; although, improved central electron confinement (ICEC) has been reported in Ohmic plasmas with off-axis ECH and counter-CD on-axis[8]. In the fully sustained plasmas described in this work, adding additional ECH or, especially, counter-CD in the plasma center demonstrates that an electron internal transport barrier (eITB) exists due to the combination of the off-axis CO-CD and bootstrap current. The electron energy confinement time τ_{Ee} in non-disruptive plasmas exceeds the RLW confinement time τ_{RLW} by up to a factor of 4.5 (i.e $H_{RLW} \equiv \tau_{Ee} / \tau_{RLW} \leq 4.5$). When the central counter-CD is increased beyond a certain point, the pressure profile becomes too strongly peaked, the plasma is MHD unstable, strong mode activity is observed and the good confinement is lost. However, by controlling the amount of central counter-CD, it is possible to stay just below the instability limit. The eITB is controlled by the off-axis ECCD deposition location. When additional ECH power is added inside of the barrier, the pressure profile peaks, the BS current increases, the eITB is reinforced and the bootstrap current increases further. It might be expected that the total

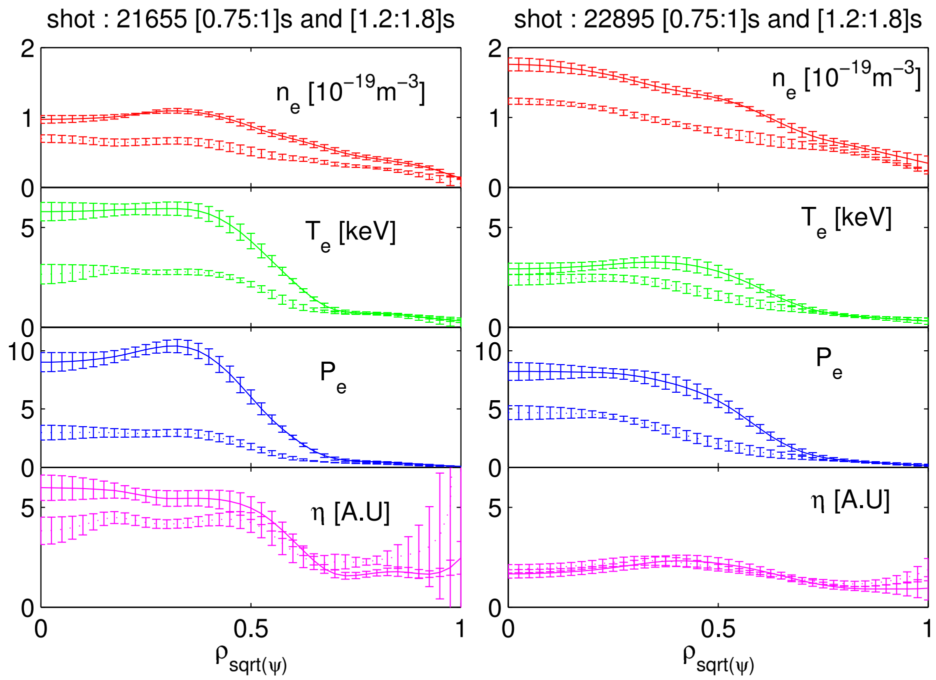

Figure 3. Electron density, temperature, pressure and CD efficiency related Te/ne for 2 high bootstrap fraction shots before and after the addition of central ECH and counter-CD. The off-axis CO-CD power deposition is centered near normalized radius of 0.6. Bootstrap fractions of 50% (21655) and 76% (22895) are calculated for plasma currents of 90kA and 70kA, respectively. The higher density of 22895 reduces the current drive by a factor of 2 prior to the central heating but ultimately increases bootstrap fraction.

current would increase accordingly. However, in general in TCV the average density rises as the ECH power is increased. The local ECCD efficiency is proportional to T_e/n_e while the BS current is proportional to the gradients of n_e and T_e. The constant of proportionality for the density is ~2-3 times as large as for the temperature[9]. When T_e/n_e remains constant as ECH is added inside the barrier, the BS current can increase while the ECCD current does not change. In this case, the bootstrap *fraction* will increase with additional ECH power. In the case of counter-ECCD added inside the barrier, the ECCD current can even decrease. Thus, the total plasma current (ECCD + BS) need not increase significantly even when the bootstrap current increases.

The electron density, temperature, pressure and current-drive-efficiency related ($\eta \equiv I_{CD}/P \sim Te/ne$) profiles are shown from top to bottom in Fig. 3. Two shots are shown; 21655 (left) at low density ~0.6 x 10^{19} and 22895 (right) at twice the density. Initially, 0.9MW of off-axis CO-CD sustains the current and the profiles evolve on a current redistribution timescale (few 100ms). Once the current has evolved, 0.45MW of counter-CD is added inside the barrier. In shot 22895, an additional 0.45MW of ECH heating power was added to each phase of the shot to permit higher density operation. The total power was 1.4MW for shot 21655 and 2.3MW for 22895. The lower curves are averages over ~200ms prior to the addition of power inside the barrier and the upper curves are averaged over ~800ms during the central heating phase. The change in profiles occurs during a few tens of milliseconds. The CO-CD is deposited around $\rho \sim 0.5 – 0.6$ in shot 21655 and $\rho \sim 0.6–0.7$ in shot 22895. The current drive efficiency remains nearly constant when the additional power is added, except in the central part of 21655 where the counter-CD occurs.

Conclusions

Plasmas have been fully sustained by off-axis ECCD. The driven current profile is flattened by radial diffusion of the fast electrons. Large bootstrap contributions to the total current profile produce steady state reversed shear profiles exhibiting steady-state eITBs. Bootstrap fractions of up to ~80% are acheived by proper distribution of 2.3MW of power.

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