On the ECCD current density profile with particle diffusion in eITBs and its impact on the q-profile

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Abstract. The Fokker-Planck code CQL3D has been used to investigate the effect of radial particle diffusion on ECCD current density profiles in the TCV tokamak. For two discharges with electron internal transport barriers (eITB), the j_{cd} and the resulting q-profile have been calculated and reconstructed. The studied eITBs are of two kinds: fully sustained non-inductive eITB with off-axis co-current ECCD, or with a large Ohmic current and on-axis counter ECCD. It is shown that different diffusion profiles do modify the ECCD current density profiles, but that the resulting q-profiles are less influenced due to the resulting necessary self-consistent inductive current contribution.

Keywords: ECCD, CQL3D, diffusion, current reconstruction, q-profile
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INTRODUCTION

It is generally acknowledged that the q-profile, and more specifically the magnetic shear can reduce heat transport in tokamak plasmas. Especially for the understanding of the development and sustainment of internal transport barriers, these two factors play a key role. As it is difficult, at best, to measure these quantities experimentally, a theoretical approach is useful to determine them.

With the total current density profile inversely proportional to q, it is necessary to reconstruct all components of the current. The ohmic and bootstrap contributions pose no major problems in this respect, since they can be calculated from other measured quantities, like the surface loop voltage (steady-state required) and the temperature and pressure profiles. If on the other hand, a non-negligible part of the current stems from the electron cyclotron current drive (ECCD), its current density profile (j_{cd}) has to be calculated using the standard Fokker-Planck equation. In this article we have in this regard employed the three-dimensional, quasi-linear code CQL3D[1], which solves the bounce-averaged Fokker-Planck equation.

The importance of particle diffusion for reconstructing the j_{cd} in TCV (Tokamak à Configuration Variable) was displayed by R.W. Harvey[2]. It was shown that a reduction of the reconstructed total I_{cd} in TCV from 550kA to the experimental 100kA was obtained by adding a radial particle diffusion to the standard Fokker-Planck equation. The particle diffusion plays a stronger role for current reconstruction in TCV than in e.g. DIII-D, due to its compact size and high electron cyclotron (EC) power density[2].

The radial particle diffusion decreases the ECCD efficiency from its maximum quasi-linear value as it reduces the supra-thermal tail which leads to that fewer electrons can interact with the waves. The diffusion of the supra-thermal electrons implies, in addition, that they can be transported out of the wave-particle interaction zone carrying a noteworthy current. This broadens the EC current density profile, which creates the possibility to have fully non-inductive discharges in TCV. It is nevertheless important to note that the predicted EC efficiencies are still higher than their linear values.

In brief, this work investigates the effect of radial particle diffusion in a series of simulations of the ECCD current density profiles using CQL3D. The total current densities are reconstructed and their q-profiles calculated. A comparison of the q-profiles from each simulation shows that the q-profiles are quite resilient to the variation in the ECCD current density profiles.

SIMULATION CONSTRAINTS

In principle a theoretical model of the $j_{\rm cd}$ ought to give an accurate result, since ECCD physics is relatively well understood. However, with a large power density, quasi-linear effects are important and the deviation of the electron distribution function from a Maxwellian becomes significant. In TCV, this means that radial diffusion has to be included in the self-consistent calculation of the wave-particle interaction, i.e. in the Fokker-Planck equation. Although it is known that anomalous transport leads to significant radial particle transport, it is not yet clear how to include it in the Fokker-Planck equation. Therefore, some freedom exists in the choice of the diffusion operator and its radial and/or velocity dependence[3]. This is why one needs to study the effects of these variations on the ultimately predicted q-profile. We also need extra constraints in order to reduce the degrees of freedom and to test the validity of the models used.

The total plasma current

In experiment, the total plasma current,

$$I_{\rm p} = I_{\rm ohm} + I_{\rm bs} + I_{\rm cd} \tag{1}$$

is measured accurately, normally within a couple of kA. Assuming steady state, the surface loop voltage and neoclassical effects give the inductive current $I_{\rm ohm}$, whereas the plasma profiles through neoclassical theory yield the bootstrap current, $I_{\rm bs}$[4]. As these three currents are known, the total driven EC current, $I_{\rm cd} = I_{\rm p} - I_{\rm ohm} - I_{\rm bs}$, is easily determined which poses a constraint on the reconstructed $j_{\rm cd}$ current density profile.

Naturally, in discharges that are not in steady-state, the inductive current, $I_{\rm ohm}$, is not accurately known. Similarly when the effective plasma charge, $Z_{\rm eff}$, is not well determined, the error in $I_{\rm ohm}$ becomes significant. However, if the contribution from $I_{\rm ohm}$ is small, then $I_{\rm cd} = I_{\rm p} - I_{\rm bs}$ is well ascertained.

Determining the particle diffusion profile

The main reason for adding a particle diffusion profile in CQL3D is to lower the efficiency of the ECCD from its maximum quasi-linear value to make it match the I_{cd} given by equation (1).

As mentioned above, particle diffusion does occur in tokamaks, but as of now there is no first principle model that can be included in the Fokker-Planck equation. Therefore, an ad-hoc empirically based term is used[3].

The particle diffusion is usually assumed to be proportional to the electron heat diffusivity, which is determined by power balance calculations[5]. In CQL3D the proportionality constant is then adjusted until the desired I_{cd} is obtained. A problem with this approach is that the power balance diffusivity is only well defined outside the region where the heating is applied. A second parameter of freedom thus enters the diffusivity profile shape, i.e. the core diffusivity level, since there is no significant central heating. This parameter can then also be adjusted in the CQL3D simulations. There is nevertheless a limit to the core diffusivity level, as it reduces the ITB barrier strength if it is set too high.

A second option that is proposed here is to tailor a diffusion profile out of the electron temperature profile measured by the Thomson scattering diagnostic. The idea would be to assume that the diffusion is high where the temperature profile is flat and that it is low where the temperature profile has a steep gradient. This will result in a piece-wise constant diffusion profile, where the height of each piece has to be determined to reduce the degrees of freedom to two or three. The tailored diffusion profile should thus not only reproduce the target I_{cd}, but also the general shape of the electron temperature. Another useful constraint would be to compare with ECE measurement, since it would provide a physically correct range of the non-thermal part of the distribution function. However, this is out of the scope of the work presented here.

METHOD

The aim of this investigation is to determine the possible spread in the q-profile one can obtain using different, but plausible, particle diffusion profiles for the reconstruction of the j_{cd} profile with CQL3D. Two shots from TCV have been used for this purpose, shot 28873 with off-axis ECCD and shot 31188 with on-axis counter ECCD. These two shots well represent the two kinds of eITB's that develop in TCV, as was mentioned in the introduction.

During the CQL3D simulations, the density was kept fixed and equal to the measured profile. The various diffusion profiles only affect the temperature profile and the EC current density profiles. The particle diffusion and relative levels in the case of a tailored profile were scaled until the target I_{cd} was reached. A certain spread in the obtained values of the I_{cd} was allowed for, to take into account uncertainties in the measurements of the effective charge, loop voltage, profile gradients etc, needed in the calculations of I_{ohm} and I_{bs}.

When all the j_{cd} profiles were reconstructed they were used together with the measured value of I_p as input into the ASTRA code[6]. ASTRA then calculated, self consistently, the profiles of j_{ohm} , j_{bs} and the safety factor.

RESULTS

Using the constraints and method described in the previous section a range of j_{cd} profiles were obtained for TCV shots 28873 and 31188.

Off-axis ECCD: TCV shot 28873

In the fully non-inductive experiment of TCV shot 28873[5], three ECRH launchers were used. With each at full capacity at 0.5MW, a total of 1.5MW off-axis ECCD was obtained. At the time chosen for analysis, t=1.15s, this shot was in steady state.

The tailored (solid) and power balance (dash-dot) diffusivities are shown in figure (1) (left). For the tailored diffusivities, the on-axis diffusion level was held constant and only the two outer levels were scanned. The diffusion was tailored so that in the flat temperature regions of figure (1) (right), the diffusion is high enough to level out the temperature profile. In the steep gradient region a small diffusion level was applied. Comparing the solid lines with the Thomson data points in figure (1) (right), the foot of the eITB is correctly reproduced by the tailored diffusion (left).

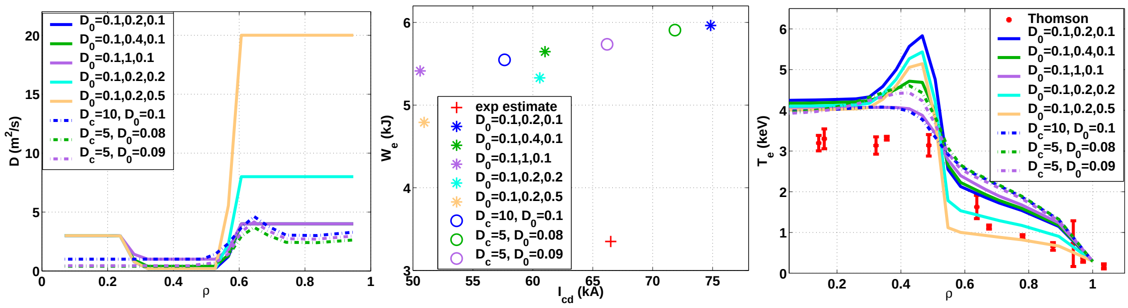

FIGURE 1. CQL3D simulations for TCV shot 28873 @t=1.15s: Input diffusion profiles (left), resulting electron energy vs I_{cd} (middle) and temperature profiles (right). The experimental value of W_{e} is calculated from Thomson data and the experimental I_{cd} is calculated with equation (1). W_{e} and T_{e}, except Thomson measurements, encompass both thermal and suprathermal energy. Moreover, T_{e} in CQL3D is calculated from $W_{\mathrm{e}}(\rho)$. In the legend the three values of D_0 refer to the constant of proportionality in each of the three regions of the tailored diffusivity. For the power balance diffusion, D_c is the minimum value of the heat diffusivity and D_0 is the constant of proportionality used to obtain the particle diffusion.

Figure (1) (middle) shows the total simulated electron energy, W_{e}, versus the I_{cd} from CQL3D. For the experimental estimate, it was assumed that $Z_{\mathrm{eff}} = 3$. As the I_{ohm} in equation (1) is inversely proportional to Z_{eff}, its value will normally have a direct influence on the expected I_{cd}. TCV shot 28873 is fully non-inductive with a small ohmic current, $I_{\mathrm{ohm}} \sim -5$kA, thus varying Z_{eff} does not lead to any significant change in the expected I_{cd}. The total value of the electron energy, W_{e}, includes both thermal and suprathermal electron energies and therefore has to exceed the experimental value measured with Thomson scattering.

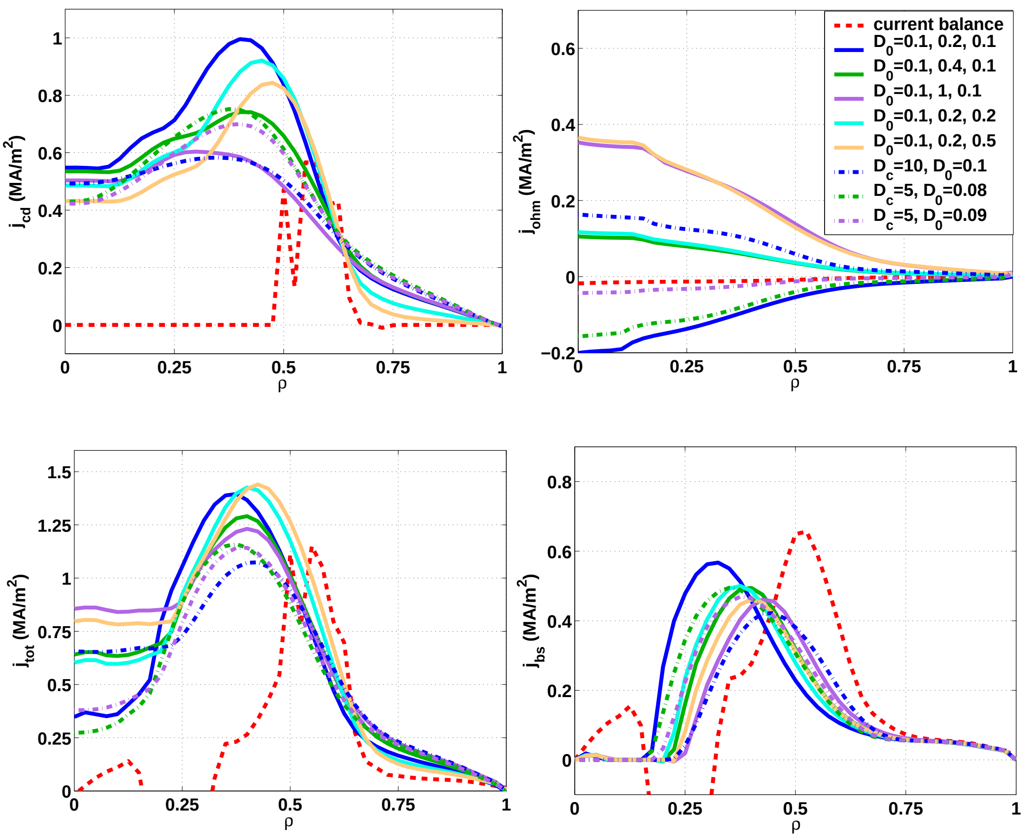

FIGURE 2. Astra results for TCV shot 28873 @t=1.15s: CQL3D j_{cd} (top left), ASTRA j_{ohm} (top right), ASTRA j_{tot} (bottom left), ASTRA j_{bs} (bottom right). The current balance values are experimental estimates of the different current profiles, except for the j_{cd} which is calculated from linear theory.

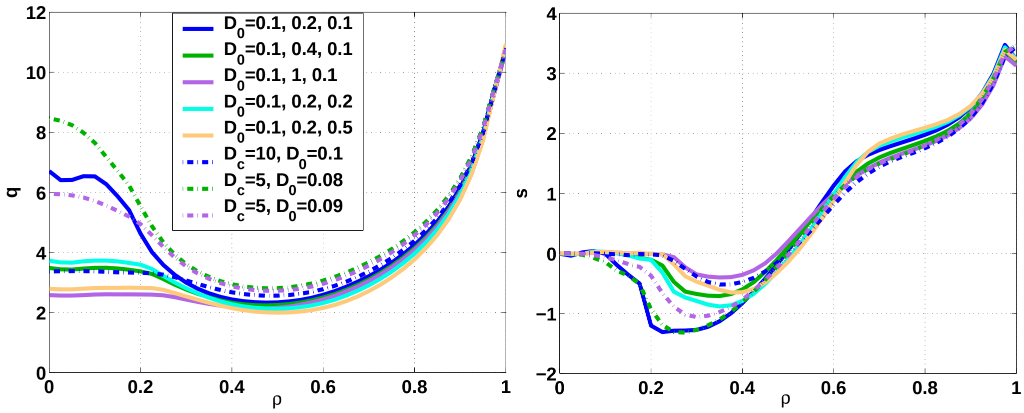

FIGURE 3. Astra results for TCV shot 28873 @t=1.15s: q-profile (left) and magnetic shear (right).

The different diffusion profiles of figure (1) (left) gave rise to an I_{cd} ranging from 50-75kA in CQL3D. The j_{cd} profile shape changes as well (figure (2), top left). In the same figure, the linear j_{cd} indicates the spatial region of the non-linear current drive. The added diffusion smears out the j_{cd}, which nevertheless peaks off-axis.

ASTRA runs of the EC current density profiles from CQL3D in figure (2) (top left) gave the j_{ohm} , j_{bs} and j_{tot} shown in figure (2) when I_{p} was kept fixed to its experimental value of 97kA. As the values of the I_{cd} from CQL3D varies from case to case between 51 – 76kA, ASTRA changes the loop voltage to create an ohmic current between -10 – 18kA, in order to obtain the target I_{p}. This gives rise to the spread in j_{ohm} (top right) and, to a lesser degree, in the total current density profiles (bottom left). The bootstrap current (figure (2), bottom right) produces $28 < I_{\mathrm{bs}} < 33$kA, due to the changing q-profile, which also has to be compensated for.

Figure (3) shows that the differences in the q- and s-profiles are small outside the normalized minor radius $\rho = 0.4$. The minimum value of q is located near $\rho = 0.5$ and ranges from 2.0 – 2.8, whereas on-axis 2.5 < q(0) < 8.5. This can be compared with the spread of the j_{cd} at these points, 0.46 – 0.86MW/m^2 and 0.42 – 0.55MW/m^2. However, the range of j_{tot} at $\rho \sim 0.5$ is only $1.05 \pm 20\%$MA/m^2 once all self-consistent constraints are taken into account. Note that if a series of experiments were performed with the same range of the minimum value of the magnetic shear as seen in figure (3)(right), $-1.5 < \min(s) < -0.5$, a difference in transport and the height of the eITB would most likely be observed[7]. Therefore, the sensitivity of this range of magnetic shear on specific parameters, like EC power or amount of current driven, is required to better understand the link with electron transport.

On-axis counter ECCD: TCV shot 31188

In the experiment of TCV shot 31188, four ECRH launchers were used, each at full capacity at 0.5MW. This resulted in a total of 1MW on-axis counter ECCD and 1MW of on-axis ECRH. The shot was analyzed at t=1.4s during its steady-state phase.

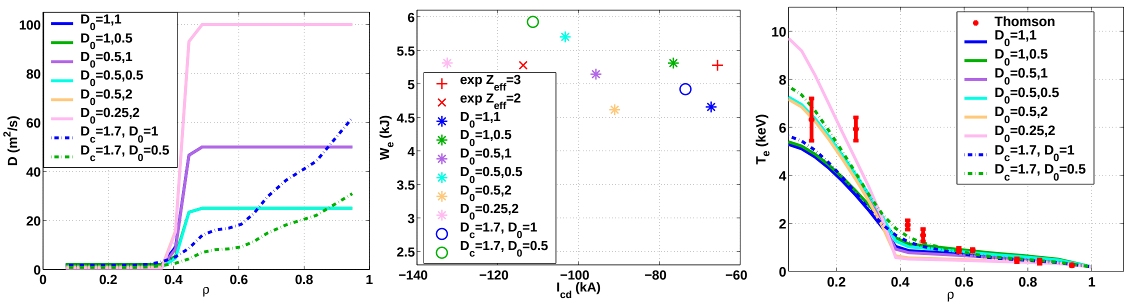

FIGURE 4. CQL3D simulations for TCV shot 31188 @t=1.4s: Input diffusion profiles (left), resulting electron energy vs I_{cd} (middle) and temperature profiles (right). The experimental value of W_{e} is calculated from Thomson data and the experimental I_{cd} is calculated with equation (1). W_{e} and T_{e}, except Thomson measurements, encompass both thermal and suprathermal energy. Moreover, T_{e} in CQL3D is calculated from W_{e}.In the legend the three values of D_0 refer to the constants of proportionality in each of the three regions of the tailored diffusivity. For the power balance diffusion, D_c is the minimum value of the heat diffusivity and D_0 is the constant of proportionality used to obtain the particle diffusion.

The tailored diffusivity for this shot (figure (4) (right)) is only made up out of two steps, as the temperature profile peaks on-axis (left). This figure also shows that the foot of the eITB is accurately reproduced in the CQL3D simulations.

In figure (4) (middle) two values are shown for the I_{cd} expected from experiment for $Z_{eff} = 2$ and 3, respectively. In TCV shot 31188, $I_p = 138$kA and we have a considerable contribution from $I_{ohm} \sim 145 - 194$kA depending on Z_{eff}, and with $I_{bs} \sim 57$kA the I_{cd} changes from -133kA to -66kA, as the diffusion is varied to span the range of total driven current. In the time interval of $1.2 \leq t \leq 1.6$s, the average value of $Z_{eff} = 2.8$, with $2.3 \leq Z_{eff} \leq 3.6$. Hence, as the inductive current is significant, there is more room for the simulated I_{cd} to vary within experimental expectations, as compared with the fully non-inductive TCV shot 28873 in the previous subsection.

Despite this less strict target value of the I_{cd} for the CQL3D simulations, obtaining a plausible result turned out to be difficult. Figure (4) (middle) shows that for an I_{cd} within the desirable range, the total electron energy in the simulations is often inferior to the energy from the Thomson measurements. Since the thermal and suprathermal energy content of W_e has to be larger than the thermal Thomson value, it appears nontrivial to reconcile it with the target I_{cd} .

Possible errors in the target I_{cd} may arise from profiles in either the loop voltage and/or the effective charge. With a high core electron temperature of almost 7keV, the plasma resistivity becomes very low. Hence, a small change in the loop voltage on-axis could drive a substantial additional ohmic current, which would imply the existence of an even more negative I_{cd} .

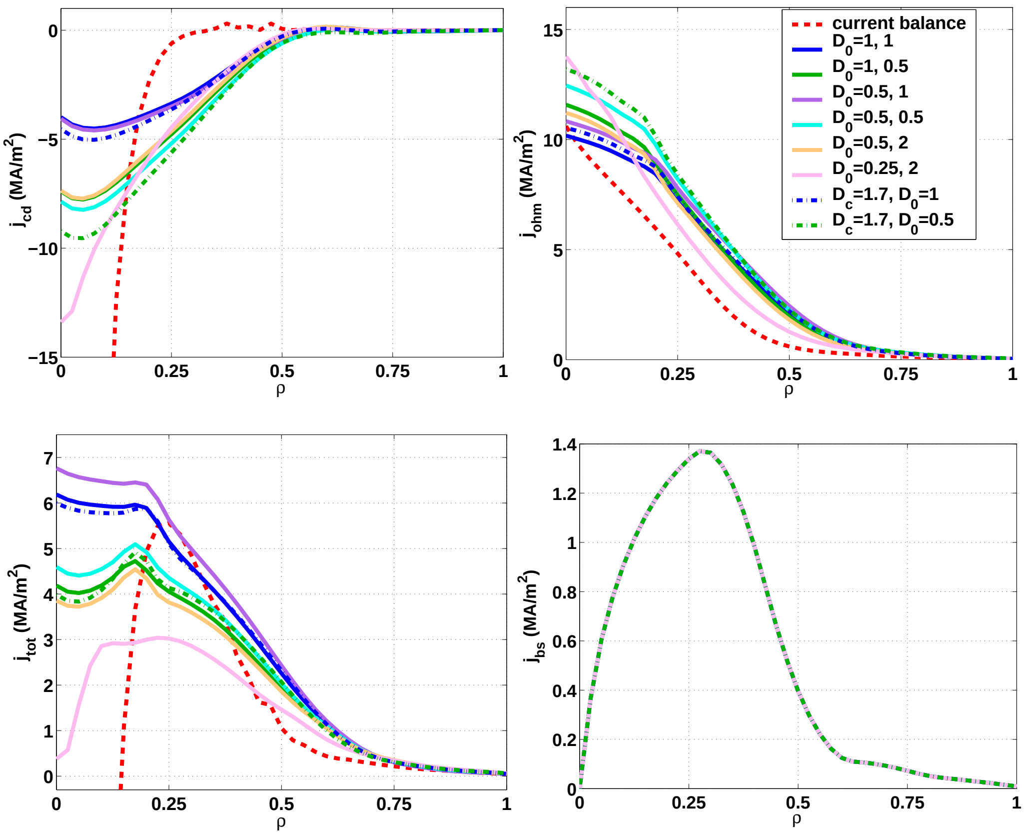

FIGURE 5. Astra results for TCV shot 31188 @t=1.4s: CQL3D j_{cd} (top left), ASTRA j_{ohm} (top right), ASTRA j_{tot} (bottom left), ASTRA j_{bs} (bottom right). The current balance values are experimental estimates of the different current density profiles, except for the j_{cd} which is calculated from linear theory.

Figure (5)(top left) shows the j_{cd} from the CQL3D simulations. The linear profile is narrow and located on-axis with a minimum of almost -56MA/m^2, much lower than the diffused, broader, quasi-linear j_{cd} . The CQL3D j_{cd} profiles are also quite self-similar.

In the ASTRA simulations the bootstrap current (figure (5), bottom right) was kept fixed at 57kA, due to problems with the trapped particle fraction. The CQL3D j_{cd} profiles and the experimental $I_p = 139$kA then produced in ASTRA the j_{ohm} and j_{tot} seen in figure (5), with $150 \leq I_{ohm} \leq 216$kA.

Disregarding the case $D_0 = 0.25$, 2, the spreading out of the j_{tot} profiles is somewhat seen in the q-profiles(figure (6), left), but it is less tangible due to the small value of q. On-axis $3.8 \leq j_{tot}$ (0) ≤ 6.8MA/m^2 and $0.34 \leq$ q(0) ≤ 0.57, compared with $1.9 <$ j_{tot} (0.5) < 2.4MA/m^2 and $0.34 <$ q(0.5) < 0.57 at $\rho = 0.5$. The absolute variation in q is constant around 0.2, but the relative spread decreases from 1.7 on-axis to 1.4 at $\rho = 0.5$.

Except for the case $D_0 = 0.25$, 2, all q-profiles cut q=1 between $\rho = 0.6 - 0.7$ and then stay below this limit. $D_0 = 0.25$, 2 has q<1 for $0.15 \leq \rho \leq 0.5$. Since no sawteeth are observed in experiment around t=1.4s, a reasonable reconstructed q-profile should have values close to or above unity. Note that the only profile that approaches this limit is with $D_0 = 0.25$, 2, which has the most negative reconstructed I_{cd} in figure (4)(middle). Further analysis is needed to understand this global mismatch of the q-profiles. Nevertheless, one can see in figure (6) that the profiles are very self-similar, even for the magnetic shear profile, at least for $\rho \geq 0.3$. This is mainly due to the very central power deposition and driven current density.

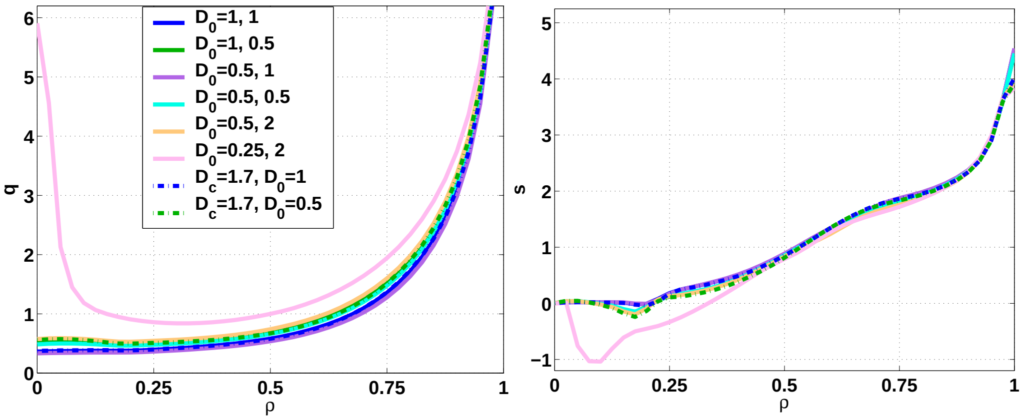

FIGURE 6. Astra results for TCV shot 31188 @t=1.4s: q-profile (left) and magnetic shear (right).

CONCLUSIONS

The effect of radial particle diffusion was studied in simulations of the ECCD current density profiles and resulting q-profiles, obtained by the Fokker-Planck bounce-averaged code CQL3D[1][3]. Two shots from TCV have been used for this purpose. Both are in steady state with an eITB, but the non-inductive TCV shot 28873 has off-axis ECCD while the TCV shot 31188 has on-axis counter ECCD. Different particle diffusion profiles have been used to investigate how sensitive the j_{cd} and q-profiles are. The j_{cd} and its total driven current, I_{cd}, have been seen to vary from case to case, but without any major impact on the safety factor or the magnetic shear. From the magnetic axis out to the mid minor radius in the TCV shot 28873, it can be seen that the minimum value of the magnetic shear varies between -1.5 to -0.5. If experiments were tailored to have such diverse shears, it would most probably affect the heat transport and lead to eITBs of different magnitudes. Nevertheless, the range of expected q and shear profiles are much better determined than one would expect by simply considering the simulated j_{cd} profiles.

The reason why the particle diffusion profiles do not influence the q-profiles as strongly as the j_{cd} is due to the reconstruction process. As a constraint the total plasma current is determined by its accurate experimental value. Therefore, a transport equilibrium code will change the loop voltage and vary the ohmic current density to match the total I_p with the various j_{cd} profiles. This leads to a change in the loop voltage and produces an ohmic current which adjusts the total current to its target level. Since $q \propto 1/j_{tot}$, this implies that if the variation in j_{tot} is constrained, so it will be for the q-profile.

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