Steady-state fully non-inductive reverse shear scenarios with electron ITB and dominant bootstrap current

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Abstract. The relation between the safety factor profile, q, the electron transport and the bootstrap current is of crucial importance for predicting advanced scenarios in burning plasmas which will have dominant electron heating and small momentum input. In recent experiments in the Tokamak TCV, the full plasma current has been sustained with only off-axis co-current drive and bootstrap current. As soon as the EC power is turned on, the inductive current is set to zero. Therefore the current profile evolves from the original ohmic profile to the one driven by the off-axis beams without any externally applied loop voltage. Due to the resulting reverse shear profile an electron internal transport barrier (eITB) is formed and the bootstrap current increases up to 50% of the total plasma current. Adding heating or counter CD in the center exhibits clear difference in the time evolution of the electron temperature profile. With less current driven in the center, and therefore a more reversed q profile, the eITB is more pronounced and better global electron energy confinement time is obtained. Increasing plasma density and EC power, electron internal transport barrier discharges with up to 80% bootstrap current have been sustained in steady-state with no ohmic current.

1. Introduction

In the last few years studies of advanced scenarios have been mainly focused on internal transport barriers (ITB) observed in the ion temperature profile and on the effects of momentum input and q profile on the barrier formation. In addition these ITBs have been obtained using fast current ramps. Electron ITBs have also been reported in several tokamaks, JET, RTP, FTU, AUG, DIII-D, JT60-U, and T10 [1], however they are usually weaker or more difficult to sustain and most of them rely on early heating in current ramp-up scenarios.

In the tokamak TCV we have been able to create electron ITBs without fast current ramp and without momentum input, solely with the help of electron cyclotron (EC) wave particle interactions. The EC beams are aimed at specific location in either heating (ECH), co- or cntr-current drive (CD), such as to create and sustain the pressure and current profiles required to obtain significant electron confinement improvement.

The experimental set-up and the typical properties of these new steady-state reverse shear eITB scenarios are described in Sec. 2. It is also shown that it is the bootstrap (BS) current which sustains the hollow current profile. The relation between these experiments and the improved core electron confinement (ICEC) discharges obtained with central cntr-CD beams and ECH off-axis pre-heating are discussed in Sec. 3. In Sec. 4 we show that even in BS dominated discharges the barrier location does not evolve, although the bootstrap current determines the q profile and the position of q_{min}.

2. Experimental set-up of fully sustained reverse shear scenarios

The tokamak TCV is equipped with a very flexible EC system which allowed stable fully sustained non-inductive discharges thanks to the ability to position the beams where desired [2]. This flexibility was also instrumental in obtaining the so-called ICEC regime with off-axis pre-heating and on-axis cntr-CD [3]. The latter regime is characterised by very peaked electron temperature, up to 14keV, and flat or slightly reversed q profile. The temperature rise in the center re-inforces the ohmic current density due to the increased conductivity. This effect has to be compensated by counter-ECCD. Thus the total current density in the center is the result of two large counter-acting components, which makes it difficult to widen the region of reversed q profile and improved confinement. Therefore a new scenario has been developed where off-axis co-CD beams sustain the full plasma current [4]. It removes the ohmic contribution and the aim was also to drive off-axis ECCD to obtain advanced scenarios. However due to the size and plasma parameters of TCV and the relatively large EC power density, radial diffusion of the fast electrons has to be considered when calculating the driven ECCD [5]. Using the CQL3D Fokker-Planck code to simulate these scenarios, it was found that the actual ECCD profile is nearly flat or slightly hollow, even though the power deposition is clearly off-axis [6]. The value of the diffusion coefficient assumed in the simulations in order to obtain the correct total driven current I_{CD} is consistent with standard L-mode confinement scaling and with the results of specific experiments using a pinhole hard X-ray camera [7]. The radial and velocity dependence of this diffusion coefficient is still under investigation [8].

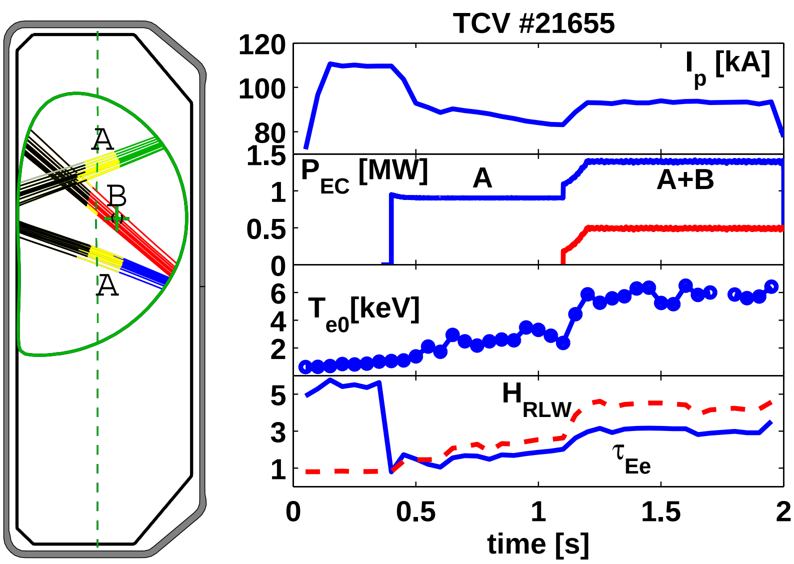


Fig. 1 (left) : Two beams off-axis in co-CD (A), then one beam on-axis in cntr-CD (B). The ohmic transformer is set constant from 0.42s. Note that τ_{Ee} increases albeit a 50% increase in input power, yielding factors $H_{RLW}\geq4$, and H_{IT98L}~1.6.

In Fig. 1 we show the typical experimental set-up of these fully sustained reverse shear scenarios. First a stationary ohmic plasma is created at low plasma current. At 0.4s two or more off-axis co-CD beams are turned on (A). The externally applied ohmic current is set to zero by imposing a constant current in the ohmic transformer as in the full ECCD scenarios [2b]. After the current profile has evolved, the second EC cluster is turned on mainly to provide central power deposition in order to probe the presence of an eITB. As seen in Fig. 1, adding 0.45MW in the center, in this case with a small cntr-CD component, leads to an increase of the electron energy confinement time, τ_{Ee}, confirming the very good confinement in the center. In general we compare τ_{Ee} with the RLW scaling law [9] as it correctly predicts τ_{Ee} during ohmic heating, whereas the ITER98-L mode scaling [10] predicts twice the experimental value in ohmic and is not really appropriate when the ions are cold.

In Fig. 2 we show the current density profiles in the high performance phase shown in Fig. 1, 1.2s-1.8s, as calculated with CQL3D using $I_{CD}=I_p-I_{BS}$ as a constraint to determine the diffusion coefficient [5]. We also show the BS current density, calculated from the experimental profiles and using the formulae in Ref. [11]. The resulting q profile is then obtained using the total current density and pressure profiles as source terms of a fixed boundary equilibrium code, Fig. 2(b). It is interesting to note that the q profile obtained from the magnetic reconstruction, LIUQE, is very similar over most of the minor radius [4b].

As mentioned earlier these scenarios are obtained with no momentum input. In addition as it is argued that the q profile modification is sufficient to create the eITB, we expect the rotation profile to be insignificant with respect to the barrier formation. This is confirmed by the rotation profile measured by the CXRS diagnostic [12] in a scenario similar to the one presented in Fig. 1, but positioned at z=0 to allow better radial coverage. It shows that the rotation actually decreases with respect to the ohmic profile when the EC is turned on. It is essentially flat in the high performance phase as well, similar to T-10 observations [1c]. The ion temperature profile is also shown in the three different phases. During the latest phase, T_{e0}~6keV and T_e/T_i~30 even though it is often assumed that large T_e/T_i ratios prevent eITB formation.

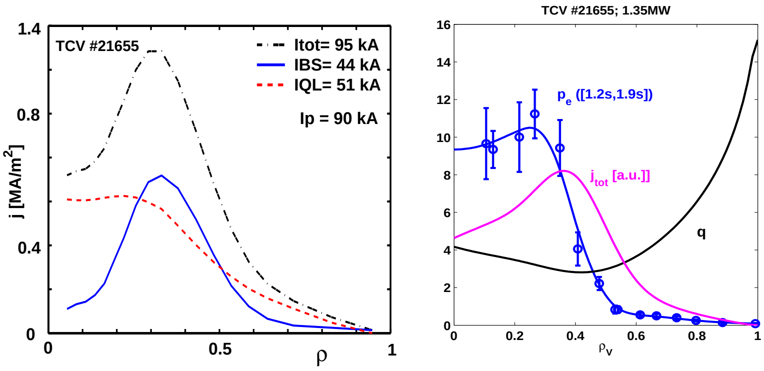


Fig. 2 (bottom): (a) EC, BS and total current density in the [1.2s,1.8s] phase of the discharge shown in Fig. 1.
(b) Resulting q profile, with j_{tot} and p_e profiles.

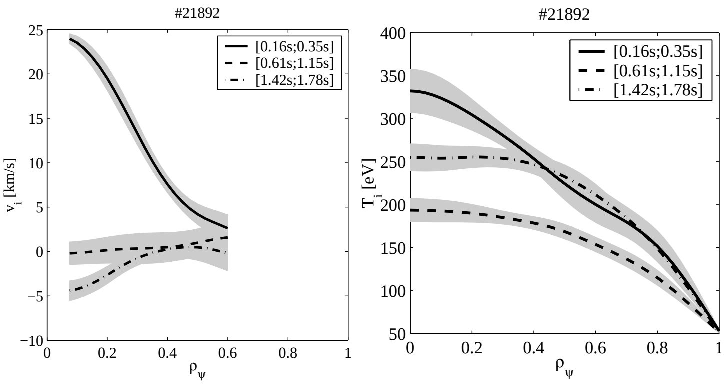


Figure 3: Ion toroidal rotation and ion temperature profiles for a case similar to the #21655 shown in Fig. 1. Profiles in ohmic, off-axis beams and cntr-CD on-axis phases are shown respectively

3. Electron ITB with and without a large ohmic current density

In previous experiments at larger plasma current, ICEC was obtained using off-axis and on-axis beams as mentioned earlier [3]. In this way stationary scenarios with confinement factors above 3 have been obtained. In Fig. 3, the profiles of a fully sustained reverse shear scenario, with P_{EC}=2.2MW, similar to the one in Figs. 1 and 2 with 70-80% BS current are compared with profiles obtained in an ICEC regime as described in Ref. [3] with 2.2MW. Both cases exhibit large localised gradients, however the former has a much broader eITB, which also explains the much larger BS current density. Note that the relative confinement is larger in #22895 due to the broader region of improved transport, however τ_{Ee} (~5ms) is greater for the ICEC case, #19425, due to the larger plasma current (200kA) and density.

In Ref. [3] it was conjectured, based on successful transport simulation and prediction using PRETOR, that the improved confinement was due to reverse shear in the center with a q_{min} value near 1. However the total current density in these cases is difficult to determine as it is the result of the difference of two large contributions: the central ohmic current density, very peaked due to the peaked Te profile (Fig. 3b, #19425), and the central counter ECCD. In the fully sustained reverse shear scenarios, the improved confinement is clearly due to the q profile and occurs in the region of flat and negative shear (Fig. 2). It confirms the effects described in Ref. [3] and explains why the eITB is much narrower since q_{min} is around ρ~0.2

in these cases. However it provides a nice comparison of profiles with different q_{min} position and absolute value.

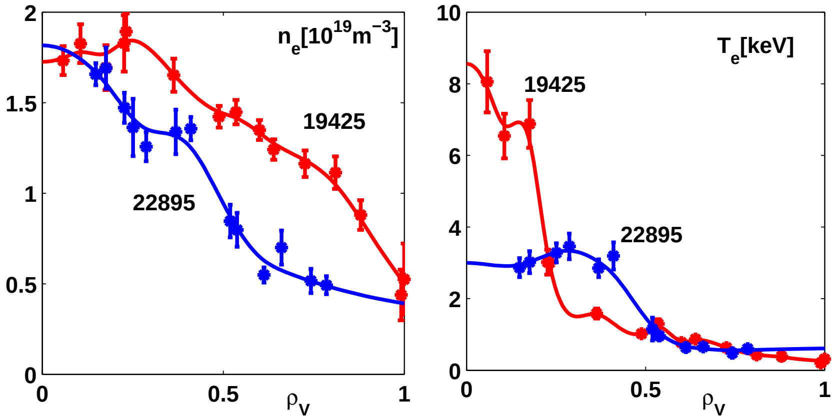
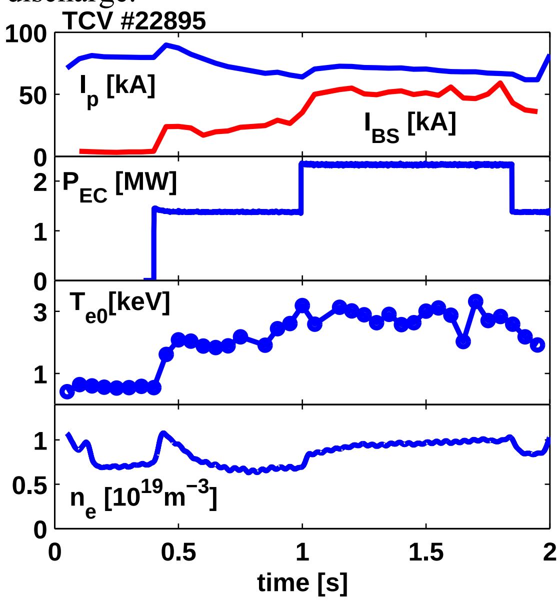


Figure 4: Density and temperature profiles for an ICEC scenario, #19425, and an off-axis co-CD fully sustained reverse shear scenarios, #22895.

The fact that the ICEC scenario, #19425 in Fig. 4, has a large ohmic current contribution, whereas #22895 is fully non-inductive does not seem to influence the effect on electron transport. However, as mentioned above, a too large residual loop voltage will drive a large current peaked in the center in such scenarios due to the large central electron temperature induced by the improved confinement. This will in turn make it difficult to maintain a reverse shear profile and may lead to a "power threshold" to overcome this effect. On the other hand active feedback on the plasma current with small loop voltage allows better control of the discharge.



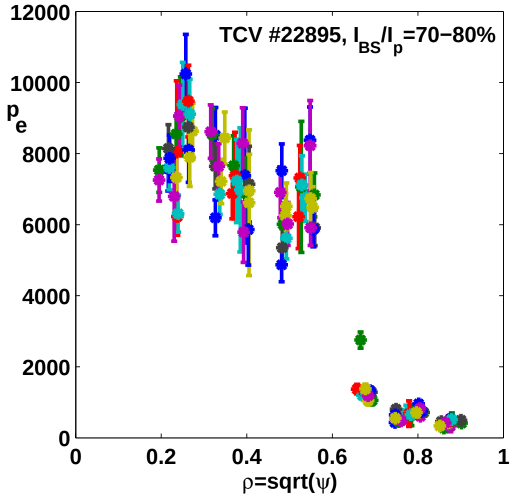


Fig. 5: Steady-state fully sustained eITB scenario with ~70-80% BS current. The ITB position does not evolve for 1.2-1.8s, as seen from p_e profiles.

4. Steady-state eITB with dominant bootstrap current

The reverse shear scenarios described in Sec. 2 are perfect candidates to test the question of bootstrap current alignment in steady-state. As the good confinement region is determined by the q profile, and the non-monotonic current profile is due to the bootstrap current, it is not clear a priori if the self-consistent profiles can be kept in steady-state. For example if the maximum pressure gradient and therefore the maximum current density is well inside q_{min}, this will lead to a new q_{min} position further inside, inhibiting the possibility of reaching a steady-state in bootstrap current dominated discharges. Therefore we have increased the plasma density and EC power in order to increase the bootstrap current fraction. Fig. 5 shows the time trace of the plasma current and bootstrap current, as well as central T_e and line-average electron density. In the first EC phase we have added a central ECH beam, as compared to the case shown in Fig. 1. Then two beams are added, one off-axis ECH and one on-axis cntr-CD, for a total power of 2.2MW. The eITB is well established as H_{RLW}~4 during the duration of the full power input, 0.6s. This is about 300 confinement times and 4 current redistribution times. The plasma current is not steady because the density is not well controlled and the ECCD is decreasing. However the bootstrap current stays nearly constant and contributes on average to 70-80% of the total plasma current. Therefore the non-monotonic current density profile is clearly sustained by the bootstrap current density. In Fig.5b we show all the density and temperature measurements between 1.2s and 1.8s. First, the barrier is very steep as it occurs essentially in between two data points (3cm apart as projected on the major radius). Therefore $R/L_{Te}\geq 30$, which is at least 3 times larger than the usual value in stiff L-mode scenarios. Second the barrier does not move at all, within the accuracy of our diagnostic, as the two groups of points at top and bottom of the barrier are well separated. We note also that there is a small barrier in the density profile (Fig. 4a), exactly at the same position as for T_e leading to a clear eITB in p_e.

4. Conclusions

New scenarios have been demonstrated for the first time where the plasma current is fully non-inductively sustained with only *off-axis* EC beams. Fokker-Planck calculations indicate that the EC-driven current is nevertheless broad and maximum near the plasma center, despite an off-axis power deposition, due to radial diffusion of fast particles. However the resulting flat or slightly reversed q profile is sufficient to create an electron ITB, which further increases the bootstrap current and therefore strengthens the barrier. In this way wide eITBs have been obtained in steady-state with H_{RLW}~4 (H_{IT98L}~1.6), with up to 80% bootstrap fraction and β_{pol}~2.

It has also been shown that even with up to 80% bootstrap current, which sustains the non-monotonic q profile and therefore the q_{min} position, the barrier location (which determines the bootstrap current position) does not move and steady-state current and pressure profiles are obtained. Note that these scenarios are obtained without momentum input nor fast current ramps. These results are important for steady-state advanced scenarios in ITER-like plasmas where the main heating source will be electron heating with low momentum input and where large bootstrap fraction are required.
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