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Electron ITB In Fully Non-Inductive Reverse Shear Scenarios

O.Sauter, R. Behn, S. Coda, I. Condrea, T.P. Goodman, M.A. Henderson, P. Nikkola

Centre de Recherches en Physique des Plasmas
Association EURATOM-Confédération Suisse, EPFL, 1015 Lausanne, Switzerland

Introduction

In the last few years the powerful electron cyclotron heating (ECH) system on the tokamak à configuration variable (TCV) has been used to modify the current density and pressure profiles in order to obtain improved performances. The performance of a tokamak scenario can be improved in many different aspects. Some of these are the energy confinement time, the plasma density, the prospective for steady-state and therefore the bootstrap current fraction, the neutron rate, the ion temperature, the ratio Te/Ti or the degree of control of the current and pressure profiles. As only electrons are heated with auxiliary power on TCV, we are not considering properties related to the ion temperature, except that we can have very high T_e/T_i ratio. In previous experiments, improved confinement has been obtained with the addition of counter-current drive (cntr-CD) in the center. First due to sawteeth suppression [1] and then with discharges pre-heated with off-axis ECH deposition in order to be able to create flat and reverse shear in the center even with a large ohmic current contribution [2]. This latter scenario, leading to improved core electron confinement (ICEC), could be sustained in a quasi-stationary state and led to very high central electron temperature (T_e~10-15keV) and peaked pressure profiles. In this way high confinement, up to $H_{RLW}=\tau_{Ee}/\tau_{RLW}$~3.5, has been obtained at relatively high plasma current and density (Note taht in this paper we shall normalise the confinement time to the RLW scaling [3] as it usually predicts well confinement properties of dominantly electron heated discharges). These scenarios, however, are inherently non steady-state, similarly to the fast I_p ramp-up in conventional advanced scenarios, as they rely on a strong ohmic current contribution.

On the other hand, using the flexible EC system on TCV in order to spread the electron heating and current drive profiles, we have been able to sustain the full plasma current non-inductively, up to 210kA, for the whole gyrotron pulse length, 2s [4, 5]. It has even been shown that the discharge could be sustained twice as long by stacking the gyrotron pulses back to back, albeit at half power and plasma current [4]. In this way we have gained a lot of experience in long-pulse discharges, with a specific feedback loop to set $I_{ohmic}=0$, and on the ways to control the pressure and current profiles in order to avoid MHD modes in particular. As the characteristic current redistribution time, τ_{crt}, is typically of the order of 0.15-0.2s in TCV and the confinement time with strong electron heating of about 2ms, at densities around $10^{19}m^{-3}$, we have sustained discharges fully non-inductively for up to 2000 τ_{Ee} and 20 τ_{crt}.

In this paper we present first results on combining these two approaches in order to develop advanced scenarios with electron internal transport barrier (eITB) and truly steady-state regimes, that is with no residual ohmic current which could compensate transient loss of current drive efficiency for example.

The existence of an eITB in fully sustained scenarios

The typical experimental set-up is the following: starting from a stationary low current ohmic plasma, two or more gyrotrons are applied in co-CD off-axis to sustain the total plasma current without leading to peaked current profiles. The confinement improves and the bootstrap current builds up leading to non-monotonic current profiles. The analysis of the driven and bootstrap current in these scenarios and of the formation of a non-monotonic q profile is described in details in Ref. [6]. After 0.6-0.8s, an additional gyrotron is applied in the plasma core in order to probe, demonstrate and evaluate the eITB and the improved confinement in the core. Such a case is shown in Figs. 1 and 2, #21654, in which 2 gyrotrons (0.9MW) of type A, Fig. 1a, are coupled to the plasma at 0.4s and one additional ECH beam on-axis (type B) is applied at 1.2s. The plasma current decreases after 0.4s, Fig. 1b, since the ohmic current is turned off with a specific feedback which keeps a constant current in the ohmic transformer after 0.42s. As the off-axis current drive efficiency is smaller than in the core, the total plasma current evolves towards about 60-80kA depending primarily on the plasma density. At 1.2s the central temperature and H_{RLW} increase rapidly, on the energy confinement timescale, up to H_{RLW}~3.5 (Fig. 3, 21654, blue). Note that, at 1.2s, τ_{Ee} stays constant even though P_{EC} is increased by 50%, which demonstrates that the plasma core indeed has improved core confinement properties. As the n_e and T_e profiles evolve rapidly, it means that the eITB is already formed, as can be seen from the T_e profile (0.8-1.05s) in Fig. 2b, and the additional central heating simply enhances it.

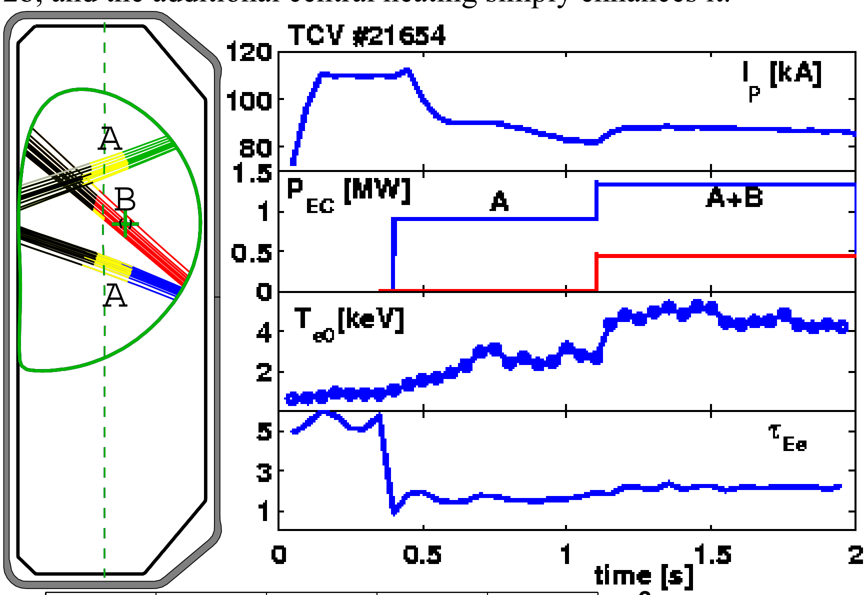
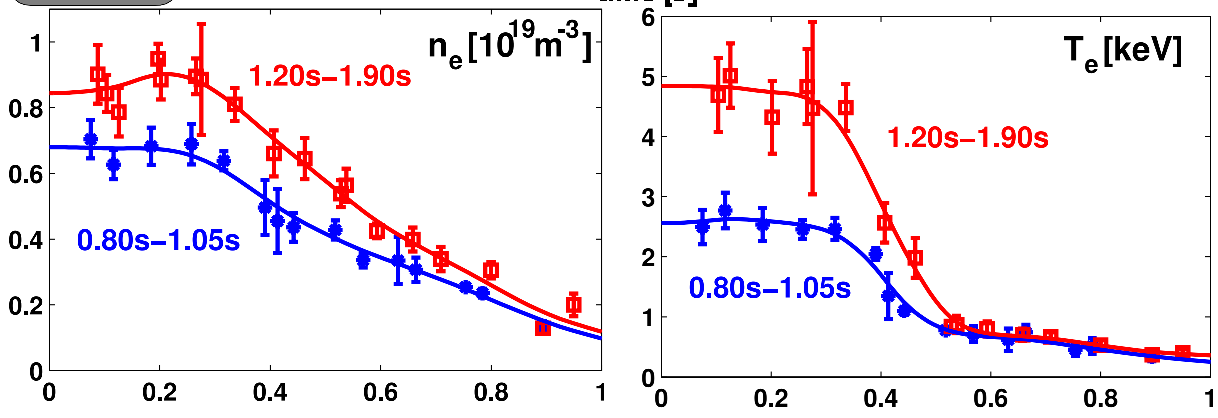


Fig. 1 (left) : Two off-axis co-CD (A), then one on-axis ECH (B). Ohmic transformer constant from 0.42s. Note that τ_{Ee} stays constant albeit a 50% increase in input power.

Fig. 2 (bottom): Profiles before and after central heating. The eITB is evidenced with the additional ECH, but exists also before.



The EC power is applied on a stationary ohmic plasma, at 0.4s, as no I_p ramp is used to form the eITB. Therefore the barrier and the improved confinement region form at some point in time, or gradually, when the current profile evolves from a peaked (ohmic) to a non-monotonic shape. In order to test if there is a sharp bifurcation, for example at the moment when the q profile becomes reversed, we compare #21654 with the discharge #21649 in which the central beam is applied from the beginning at 0.4s. We see in Fig. 3 that the confinement starts at H_{RLW}~2.3, which corresponds to standard confinement with central heating and peaked current profile [4], and evolves slowly to the steady-state value, on the current redistribution timescale. Therefore it is indeed the change in current profile which is responsible for the improvement in the core confinement. As there is no momentum input and T_i is small, about 200eV, no effects of rotation shear are expected and the eITB can be formed solely thanks to the modification of the q profile.

In order to test this result further, we have added a small oblique angle to the central EC beam in order to have cntr-CD. Already with a toroidal angle of only φ=–5°, the performance is significantly increased (#21655, Fig. 3) up to H_{RLW}~4.5 and T_{e0}~6keV. With φ=-15° the confinement is even better and it leads to overly peaked profiles, which are MHD unstable, leading to a disruption 20ms after the last Thomson data point. Note that as the discharge is fully sustained by the EC beams and the bootstrap current, we can control both the current and pressure profiles. Therefore it is easy to stay just below the ideal MHD limit and sustain an advanced scenario with a strong and wide electron ITB in steady-state without any MHD activity.

Co- versus Cntr-CD in the center

The direct relation between the confinement properties and fine tuning of the q profile has been further tested by comparing two discharges with identical beam aimings, except the central beam has opposite φ angle (+4.2° and –4.2°). That is we compare a small cntr-CD with the equivalent small co-CD in the center and therefore the same doppler shift and deposition profile. The results are shown in Fig. 4. The core temperature and H_{RLW} are higher for the case with cntr-CD in the center (#21892) than for the case with co-CD (#21893). However this latter case still has improved confinement (H_{RLW}~2.8>2) and a clear eITB. Note also that the H_{RLW} factor obtained with central ECH (φ=0) lies in between these two cases, confirming the continuous confinement improvement observed in discharge #21649 when the current profile evolves from peaked to non-monotonic. Detailed analyses are underway to determine the q profile for these cases and see if both have reverse shear, as expected due to the significant bootstrap current contribution [6].

We have also studied the effect of aiming more or less off-axis with the co-CD beams. In this way less or more current is driven and the value of q_{min} in particular can be controlled [6]. We have obtained eITBs and improved confinement for very different scenarios, except when the current is too peaked. However detailed analyses are required to quantify the range of q_{min} values spanned during these experiments. In some cases, MHD modes appear and the barrier does not form.

High bootstrap fraction and eITB position

Using almost all the X2 power available, up to 5 gyrotrons (2.3MW), we have started to optimise the discharge #21655 to increase the bootstrap fraction. We have added one ECH beam in the core and one ECH off-axis, to avoid too peaked profiles. In addition we have considerably increased the density, privileging bootstrap current over ECCD. In this way we have obtained a steady-state scenario with I_{BS}/I_p~80% and very good confinement properties, H_{RLW}~3.5, fully sustained for $1000\tau_{Ee}$ and $8\tau_{crt}$ (Fig. 5). The barrier is so sharp we cannot resolve it fully with a 3-5cm resolution. Moreover we see that the barrier position does not move even though the reverse shear is due to the barrier itself, through the local maximum in the pressure gradient. Thus there is no problem of alignment between the bootstrap current and the improved confinement region. This is in fact not astonishing from the above results which show that the electron core confinement is controlled essentially by the q profile.

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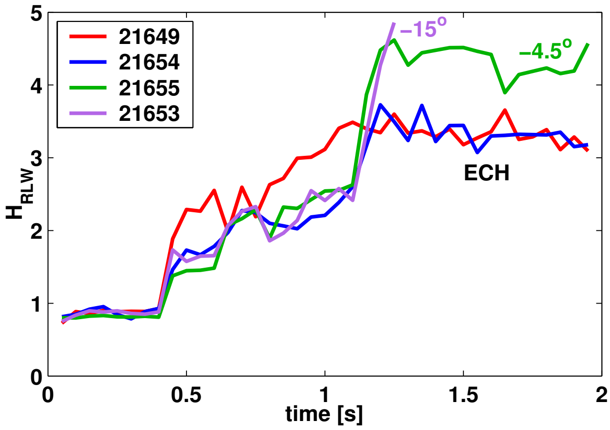

Fig. 3: Confinement factor time evolution with different angles for central beam and timings

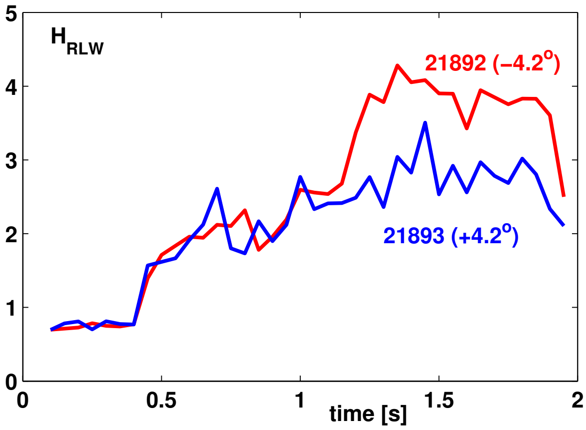

Fig. 4: Significant improvement with small central cntr-CD vs co-CD

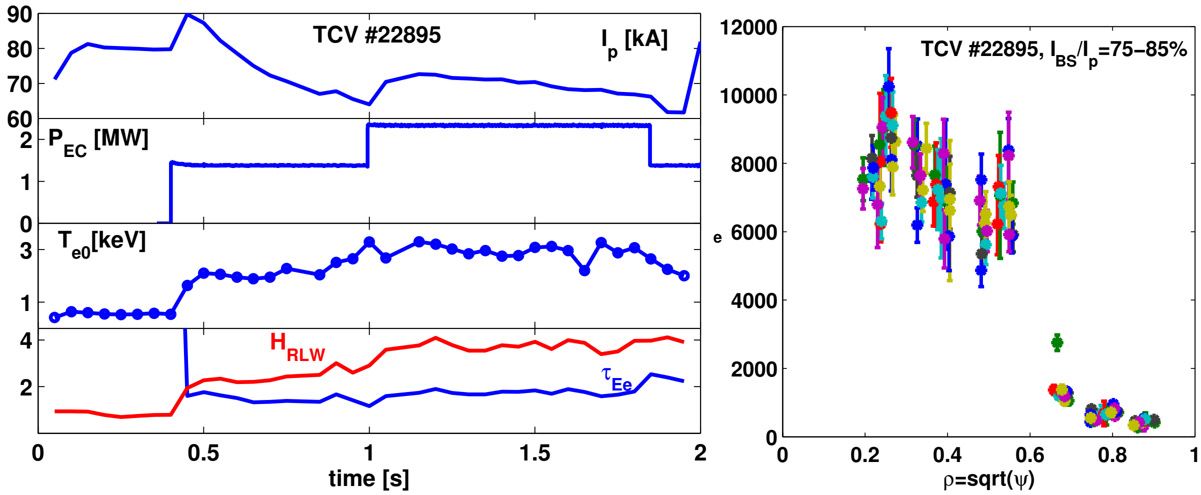

Fig. 5: Steady-state fully sustained eITB scenario with about 80% bootstrap current. The barrier position does not evolve during 1.2-1.8s, as seen from p_e profiles.