Current and Pressure Profile Control using ECCD and ECH in TCV

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Abstract

Steerable mirrors allow the change of both the poloidal and toroidal launcher angles in TCV. Both ECH and ECCD experiments have been performed in order to demonstrate the modifications of the electron temperature and current profiles. We have achieved full replacement of 153kA with central co-ECCD using three 0.5MW gyrotrons for 100 ms. However this led to very peaked pressure and current profiles which are unstable and eventually led to a disruption. Using a scenario with simultaneous on and off-axis co-ECCD we have obtained a fully non-inductive steady-state scenario sustaining 123kA, with T_{e0}=3.5keV and n_{e0}=1.5 10^{19} m^{-3} for 1.9s, more than 400 confinement times and about 4 current diffusion times, limited only by the gyrotron pulse length. We also show that a careful choice of the plasma current is needed to exactly replace the ohmic plasma current. Finally we confirm a significant current drive efficiency for far off-axis ECCD.

Results

In the last decade important progress have been achieved towards increasing the plasma confinement time, the plasma density and the value of β in stationary scenarios. In the design work for ITER, it has been shown that it is crucial to be able to keep good confinement while having both the density and β close to their respective limits [1]. This can only be achieved successfully through precise control of both the current and pressure profiles. The TCV tokamak has a powerful and very flexible ECW system [2]. At present we have three launchers of up to 0.5 MW for 2s each, which are used in the X2 mode achieving 100% single pass absorption. Each launcher has a system of four mirrors allowing a large variation of both the poloidal and toroidal angles. The first results of varying these angles are given in Ref. [3], where the formation of high energy tail electrons is demonstrated in ECCD cases. In particular, it is shown that the optimal toroidal angle for co-ECCD is around 35º, which is the angle used in this paper.

The aim of the present study is to obtain a fully non-inductive stationary scenario using three 0.5 MW gyrotrons. In order to achieve this, we need not only to sustain the plasma current by adequate current drive, but also to control the profiles so as to have a stable and quiescent plasma. Therefore one has to distribute the power deposition over the minor radius ρ in order to replace the ohmic profiles by the ones driven by ECCD and ECH. On the other hand the current drive efficiency is much larger near the magnetic axis, because of increased temperature and fraction of passing particles. Moreover, the highest temperatures are obtained when heating inside the q=1 radius [4,5]. Therefore, to obtain the maximum driven current with 1.5 MW of ECCD, one needs to have central deposition, as shown by the rays labelled 'B' in Fig. 1.
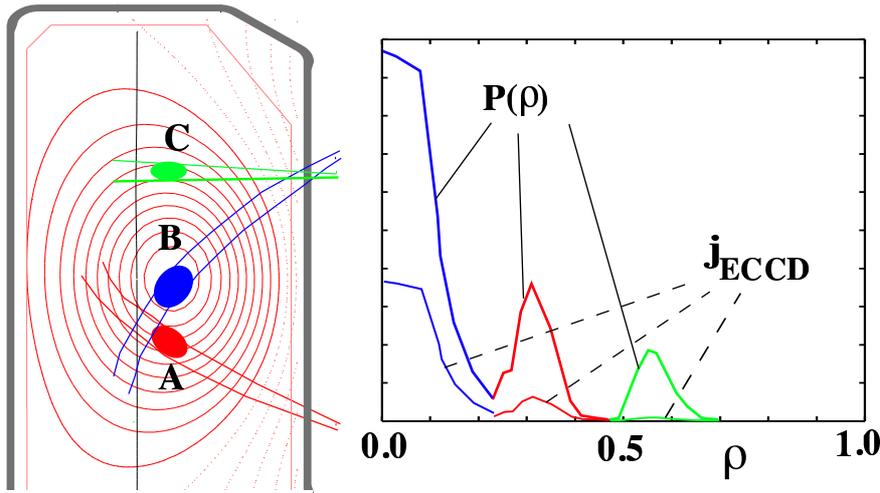
Fig. 1: a) Typical ray paths of the 3 launchers in the poloidal plane.
b) Power and current deposition profiles from Toray calculations when the three launchers are in co-CD mode with $\varphi=35^0$.

A typical result of such a scenario is shown in Fig. 2, where 153kA is fully non-inductively driven for about 100 ms, with $n_{e0}=2\cdot10^{19}$ m^{-3} and $T_{e0}=4.5$ keV, before it disrupted. In these scenarios the three gyrotrons were in on-axis co-ECCD position. As the width of the ECW power deposition is small, of the order of 10%-20% of the minor radius, it means that the resulting current and pressure profiles are very peaked. Due to these sharp local gradients, MHD modes became unstable which caused a fast disruption as in Fig. 2. Neoclassical tearing modes were also destabilized and degraded the performance of the discharge.
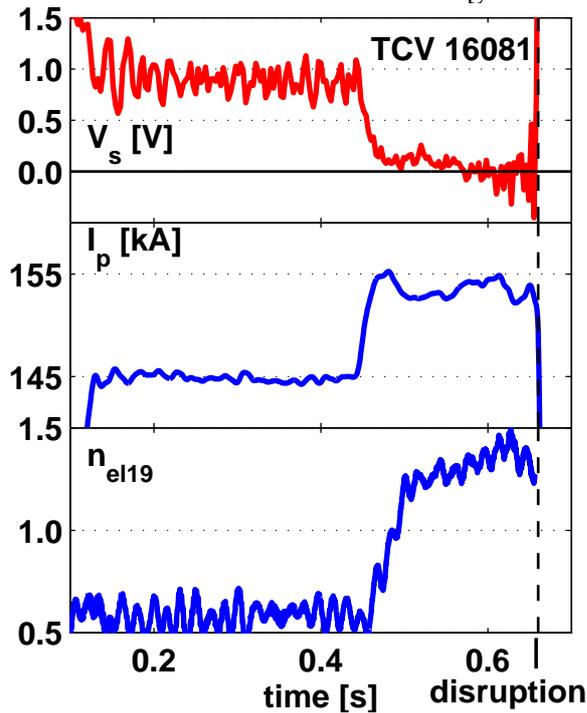

Fig. 2: Complete replacement of 153kA for more than 100 ms with 1.5MW on-axis co-CD. These scenarios disrupted due to very large gradients obtained with very peaked profiles.
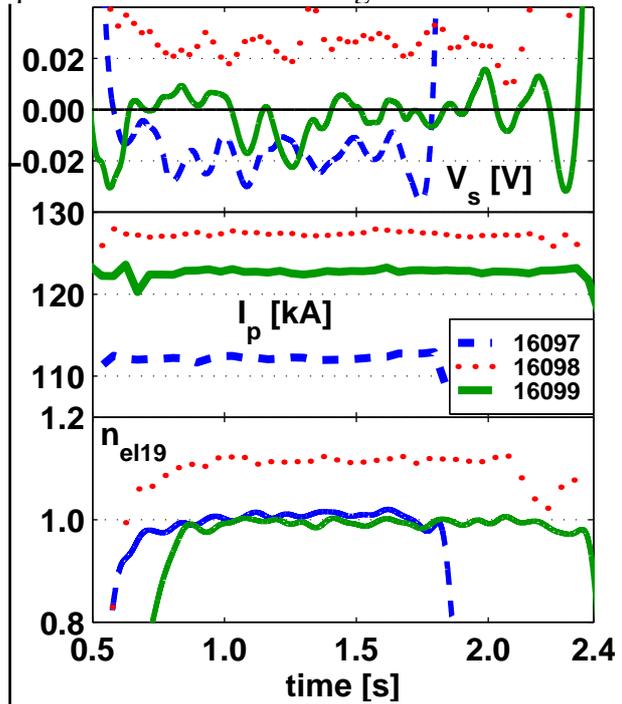
Fig. 3: Scenarios as shown in Fig. 1. The steady-state fully non-inductive scenario was obtained with $I_p=123kA$ (solid line). With I_p set to 112kA (dashed) and 127 kA (dotted), V_s was slightly changed.

In order to avoid these modes, we distributed the power deposition of the three gyrotrons over the minor radius, as shown in Fig. 1, at $\rho=0., 0.3$ and 0.55. In this case the central temperature

and the total driven current are smaller than with central deposition. However both the current and pressure profiles are broader and no MHD modes were generated. In this way we obtained a fully non-inductive discharge of 123kA for 1.9s with $n_{e0} \approx 1.5 \cdot 10^{19}$ m^{-3} and $T_{e0} \approx 3.5$ keV, as shown in Fig. 3 (solid line) and detailed in Fig. 4. In particular we show in Fig. 4b that the current in the ohmic transformer was held constant. This is the most sensitive measurement to full current replacement. As seen in Fig. 4b, V_s reached zero very soon after the ECCD was turned on, while the equilibrium profile still evolved for 0.5s (see κ, l_i in Fig. 4). We repeated this discharge with I_p=112kA and 127kA to demonstrate the exact control of the amount of current driven non-inductively (Fig. 3). In the first case (dashed line), the surface loop voltage V_s is slightly negative, indicating an excess of driven current, and in the second case (dotted line) it is positive. Taking into account the ~10% decrease in current drive efficiency in the latter case due to the density increase, these results are consistent with exact replacement at I_p=123kA and I_p-I_{CD}=11kA for $|V_s|$=0.02 V. This is also in agreement with Toray [7] calculations which give I_{CD}=120kA. However the bootstrap current generated by the peaked pressure profile obtained with ECW is non-negligible and is about 25kA, using the formulae in Ref. [8]. Therefore the ECCD is overestimated by about 20% by Toray, which is well within the uncertainties of the density and temperature profiles.
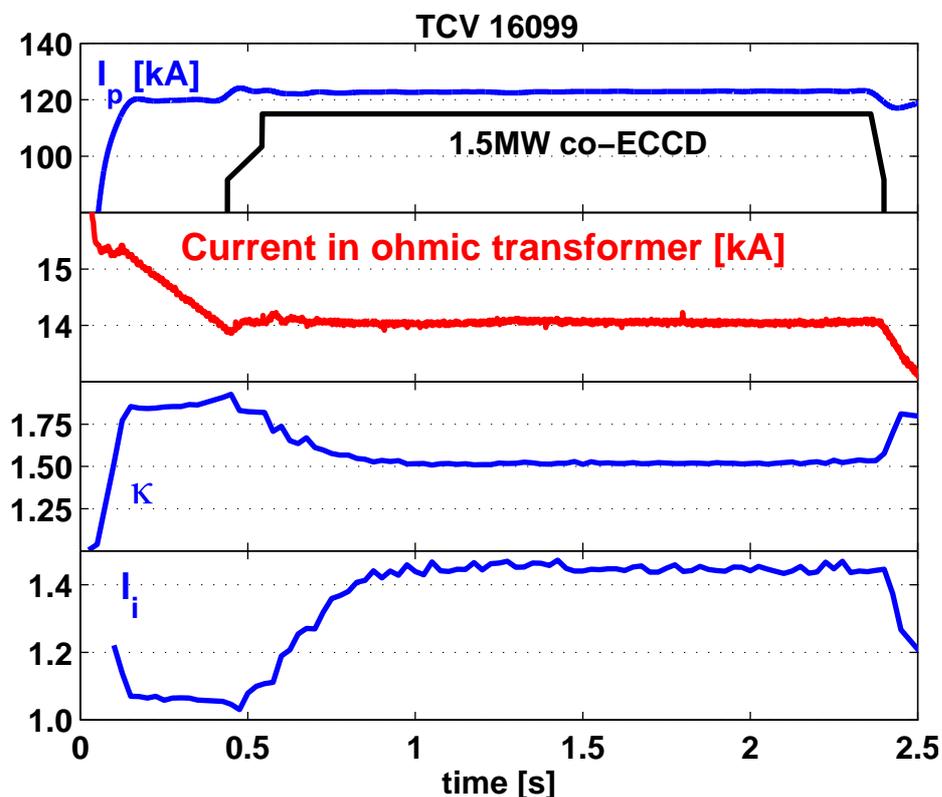

Fig. 4: Steady-state fully non-inductive discharge for 1.9s using 1.5MW of co-CD distributed over the minor radius as shown in Fig. 1.
Note that the current in the ohmic transformer is exactly constant, indicating zero inductive current in the plasma. This happens as soon as the ECCD is turned on, while the equilibrium profiles need 0.5s to settle, as indicated by the evolution of κ_{edge} and l_i.

From Toray calculations, Fig. 1b, the current driven by the most off-axis gyrotron, C, is very small, $\approx$2.5kA, near ρ=0.55. Therefore, this gyrotron seems mainly to be used to broaden the temperature profile, as the power deposited is non-negligible as shown by P(ρ). To test this we have repeated the shot 16099, but with only the two gyrotrons A and B in co-ECCD position and the third in ECH (φ=0°). This scenario is shown in Fig. 5, shot 16150. As the density was 5% higher, we repeated it with all three gyrotrons in co-ECCD, shot 16151 for a better comparison. In the first case, 16150, V_s is non-zero, about 0.02V, whereas the shot 16151 has V_s near zero ($\approx$0.005V). Therefore the current driven by the gyrotron C is important and 7-9kA are driven at $\rho \approx$0.55. This confirms the results obtained on DIII-D [9] that more current can be driven off-axis than predicted. In our case, the experimental value is only a factor of 2-3 above

the predicted value, even for $\rho \approx 0.55$, as Toray predicts a non-zero value. Note that the experimental local efficiency normalized by the local temperature, as in Ref. [9], is about 0.07 corresponding to the lower bound of the DIII-D results. However our results are obtained in a fully non-inductive scenario and in a stationary phase.

Conclusion

The ECH system on TCV has been used to obtain full current replacement in standard (positive magnetic shear) discharges. With on-axis co-CD, up to 153 kA have been fully non-inductively driven with $n_{e0}=2 \cdot 10^{19}$ m^{-3} and $T_{e0}=4.5$ keV ($\gamma_{20CD}=0.018$ A/W/m^2), 30% of the current is due to the Bootstrap current. However these scenarios lead to very peaked current and pressure profiles and eventually to disruption. With careful profile control by spreading the power deposition across the minor radius, we have obtained a steady-state fully non-inductive scenario for 1.9s, with $I_{NI}=123$kA, $n_{e0} \approx 1.5 \cdot 10^{19}$ m^{-3} and $T_{e0}=3.5$keV ($\gamma_{20CD}=0.01$ A/W/m^2, 20% bootstrap current), limited only by the pulse length of our gyrotrons. Note that this is more than 400 confinement times and about 4 times the current diffusion time.

Finally we have shown in the steady-state scenario that about 7-9kA were driven at $\rho \approx =0.55$, corresponding to $\zeta=0.07$ and 2-3 times the predicted value. This confirms the discrepancy observed by DIII-D, albeit to a lesser degree.

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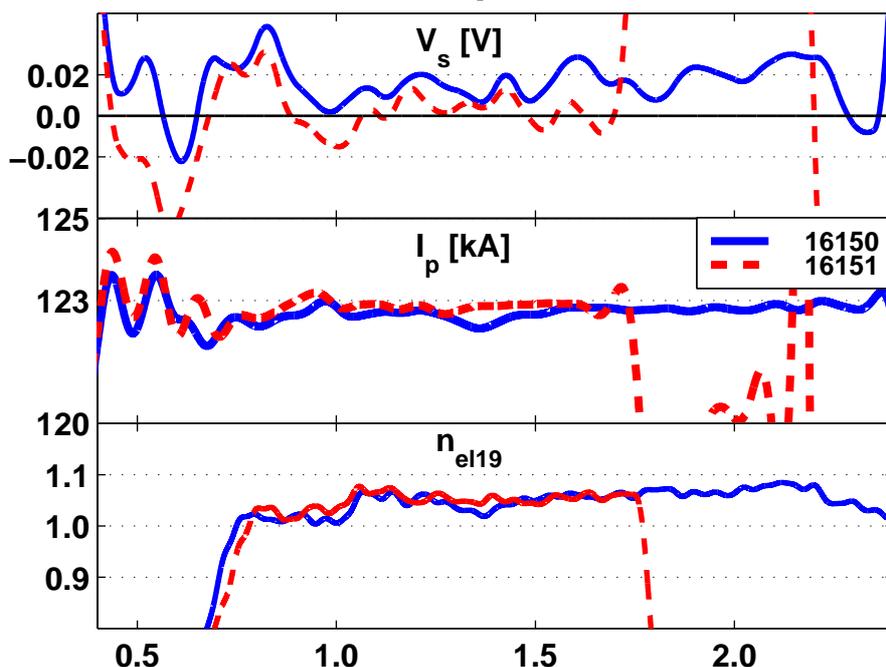9. T. C. Luce et al, General Atomics Report (1999) GA-A23018.

Fig.5: Two discharges with launchers in the same position as in Fig. 1, except for shot 16150 which has launchers A and B in co-CD and the third, C, in heating mode ($\varphi=0$). The shot 16151 has the three launchers in co-CD and is therefore identical to shot 16099 apart for the 5% change in density, to match shot 16150. This clearly shows that the very off-axis gyrotron in position C does drive current (7-9kA) as V_s is more positive for 16150 than 16151.