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Improved central confinement by current profile modification in shaped plasmas using ECRH and ECCD in TCV

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Improved Central Confinement (ICC) has been observed in TCV (Tokamak à Configuration Variable) plasmas in which sawteeth were stabilized by counter-ECCD [1]. In these cases the central electron temperature was larger by about a factor of two than with CO-ECCD or with ECRH alone. Comparison of experimental results with calculations by the PRETOR transport code indicates that sawtooth stabilization is sufficient to explain the increased confinement time and the consequent enhancement of the central electron temperature. The simulations show that sawtooth stabilization is caused by the central safety factor q_0 rising above 1 for counter-ECCD cases whereas q_0 remains below 1 in the sawtoothing CO-ECCD and ECRH cases.
ECH in TCV demands a low plasma density (the cutoff for an 82.7GHz wave is $4.25 \cdot 10^{19} m^{-3}$). Under these conditions and particularly during the electron heating phase, the ion temperature is much smaller than the electron temperature. Thus the Rebut-Lallia-Watkins (RLW) scaling law constitutes an appropriate reference for the electron energy confinement time. The experimental confinement time in ICC shots is more than 3 times higher than the global RLW scaling and is often well reproduced by PRETOR, even though PRETOR is based on the local RLW diffusivity model. Hence, current profile modification - rather than a change in the transport coefficients - is chiefly responsible for the enhanced confinement. The exceptions are shots with "prepared" low χ_e values in the central part of plasma for which experimental profiles are broader than calculated by PRETOR (see below).
Sawteeth can be more easily stabilized at low elongation (κ) and large edge safety factor (q_a). Successful stabilization has been observed with 1.35MW counter-ECCD in the plasma centre. Fig. 1 shows a comparison of temperature profiles with counter-ECCD, co-ECCD and ECRH, all with central power deposition. The maximum enhancement factor H_{RLW} in the counter case is 3.5, while it is 1.5 during co and ECRH.

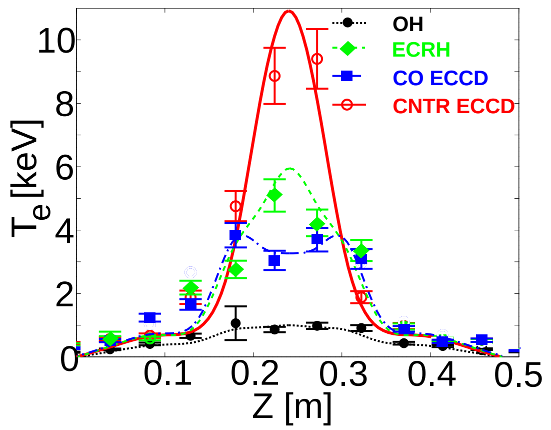
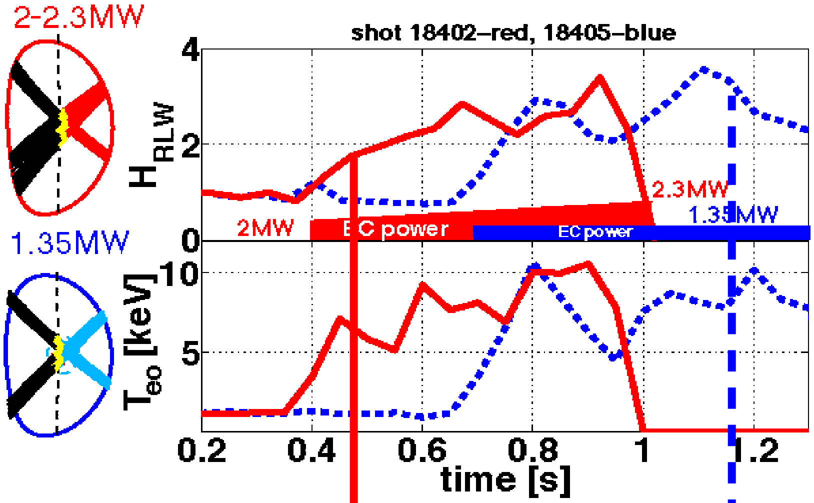


Figure 1. Electron temperature profiles along a vertical cord with counter- co - ECCD and with ECRH. An Ohmic case is shown for reference. Central power deposition. κ=1.2, δ=0.2, q_a=5.5, 1.35MW

In a more recent campaign, with additional power a larger domain of κ (up to 2.2) and q_a (down to 2.4) was investigated. Results from a plasma with κ=1.6-1.8 are shown in Figure 2, which compares two shots with counter-ECCD at the plasma magnetic axis. Confinement ex pressed by the H_{RLW} enhancement factor, is quite good in both cases in spite of MHD mode activity.

The ray tracing (TORAY) calculations shown are based on T_e and n_e experimental profiles. The beams are 100% absorbed in the yellow region and no power is transmitted to the black region.



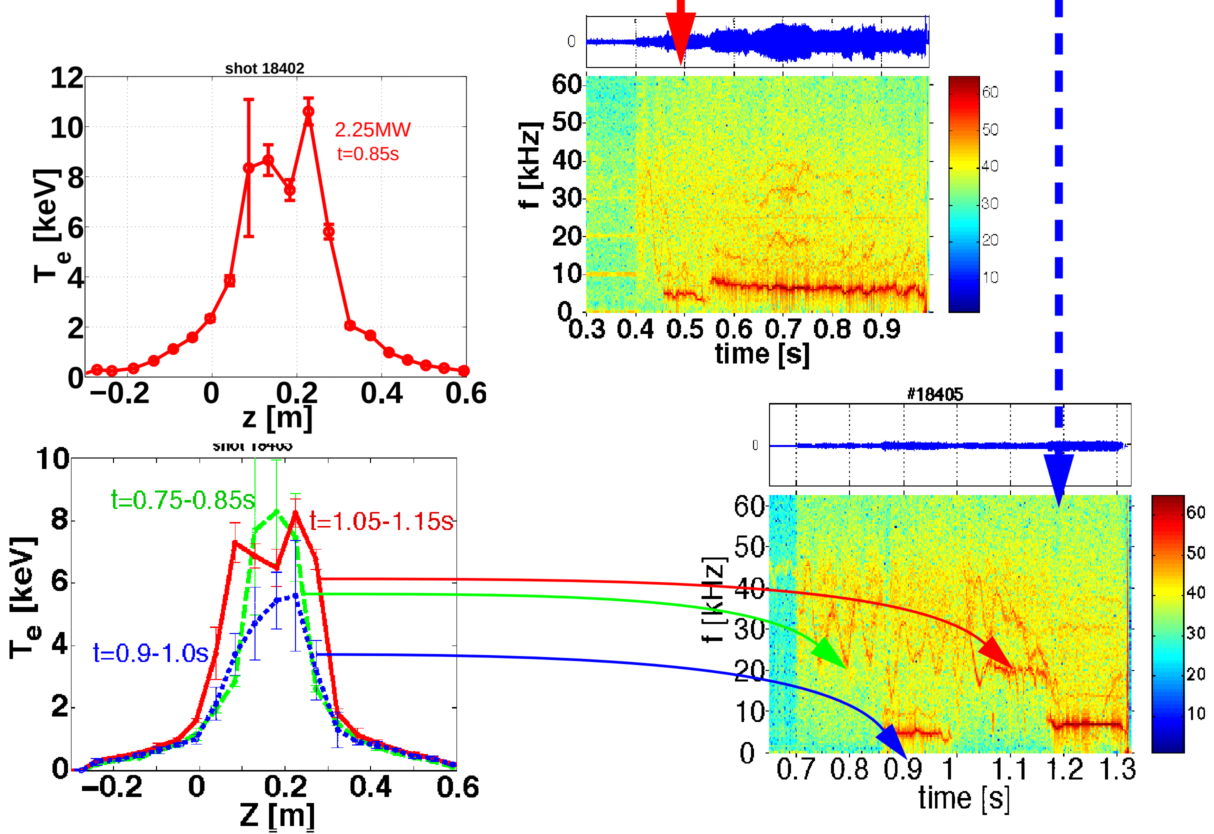


Figure 2. Comparison of two shot: one (18402) with a power ramp from 2 to 2.3 MW followed by plasma disruption, the other (18405) with 1.35MW constant power (both with counter- EC-CD). Shot 18402: κ=1.8, δ=0.3, q_a=9; shot 18405: κ=1.6, δ=0.25, q_a=7. The difference in parameters between the shots is not intentional.

However, the confinement time improves further when the low-frequency mode (~5kHz) is absent; indeed both H_{RLW} and the central temperature are well correlated with the existence of low frequency mode.In some cases it has been observed that the period of improved confinement is suddenly terminated, which is visible as a rapid decrease of the soft x-ray emissivity and collapse of the central temperature [1]. This collapse is due to an instability, since the temperature collapse is correlated with an increase in mode activity. From an analysis of magnetic probe data we could identify a high m-number mode. However, this mode is most likely coupled to an internal m=1 mode as the central temperature collapse at the appearance of this high m-number mode.

This catastrophic temperature collapse can be prevented, at least in some cases, by increasing the power in the centre gradually.
In the high κ and high q_a regime at low power there appear to exist two regimes of a good confinement as seen in Fig. 2. The time evolution from the first to the second regime is rather complex. The initial good confinement is reduced at the appearance of the mode and the central average temperature drops from 8 to 5 keV. Since the mode appears after a time of the order of the current redistribution time (~150ms), we speculate that the profile becomes too peaked and triggers instability. It is, however, unclear how the mode is stabilized later to produce a second good confinement regime with a broader temperature profile, but lower plasma density. This second good confinement regime is in turn destroyed by another mode. At higher power (2MW) and with the same central power deposition the mode starts earlier (50ms after turn on ECH). In the presence of the mode, the confinement enhancement factor appears to increase with power. The width of the temperature profile indicates that in this case we are already in the second good confinement regime. Thus, higher power can produce good confinement even in the presence of the low frequency mode.

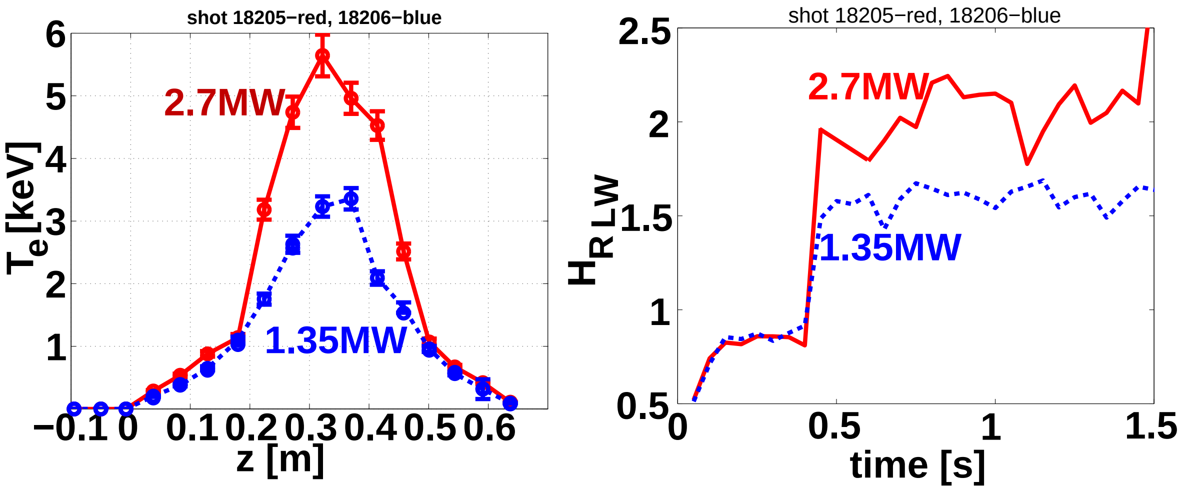


Figure 3. Changes in the temperature profile and H_{RLW} factor with power for counter-ECCD with power deposition near the magnetic axis and low q_a: κ=1.2, δ=0.19, q_a=3.1

Finnaly, we have also found that the electron energy confinement is better with counter ECCD than with ECRH with central power deposition even if the sawteeth are present. In this case the H_{RLW} factor increases with power as shown in Figure 3.

The mode activities are more easily suppress if part of power is deposited off axis either CO ECCD or ECRH mode (which one is better depends on plasma conditions). However, the enhancement factor H_{RLW} does not increase and in fact rather decreases. One of these cases (shot 18224) is shown in Fig. 4 along with a shot with all co ECCD in the plasma centre for comparison. (In shot 18224 the power was changed by a factor of two during the shot). In the shot with all co ECCD (shot18200) the plasma temperature is not as high, but energy confinement is good and the plasma is stable and sawtoothing. This shot has also a very good H_{RLW} factor of 2.5, only slightly smaller than for the case with counter on axis and 2.7MW power, but the central temperature is significantly lower.

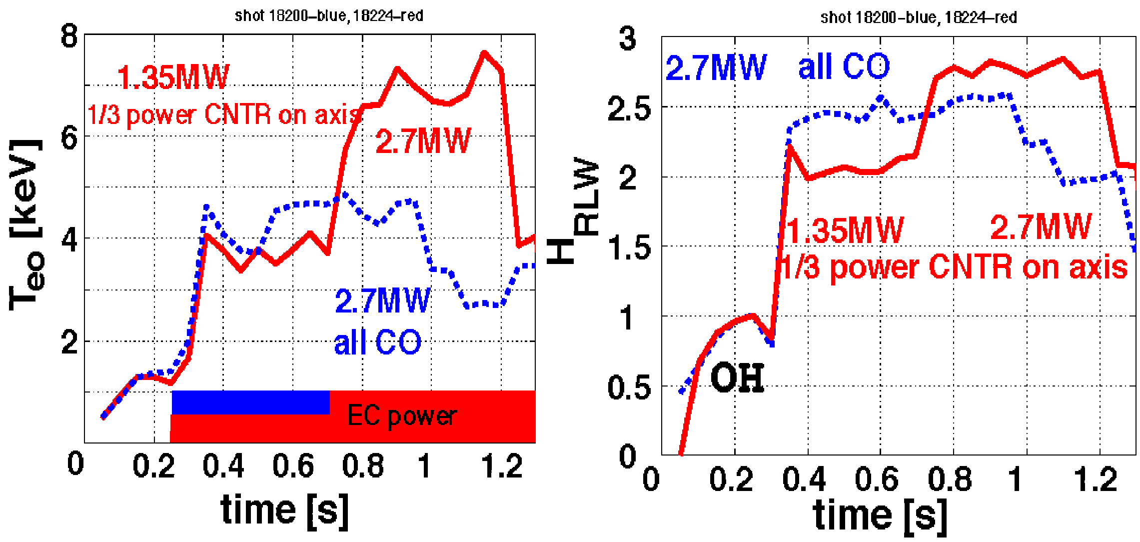


Figure 4. Shots with distributed power deposition: shot 18200 with all beams in CO ECCD direction (dashed blue), shot 18224 with two central beams in counter-ECCD direction and four off axis beams in CO direction (solid red). κ=1.6, δ=0.29, q_a=7.

The best results, so far have been observed using a scenario with power deposited in two steps ("prepared" low χ_e scenario). During the first step off axis heating or co ECCD is used to modify the current profile and obtain low (lower than Ohmic) χ_e in the central part of plasma. After a delay time (several 100ms), additional power is added in the plasma centre using counter ECCD configuration. In the first phase, with 1.35MW EC power the plasma temperature reaches 2keV and χ_e drops by about a factor of 4, owning to the lower Ohmic power in the centre. The enhancement factor at this stage is already 1.7. When the additional power is added in the centre, the central χ_e increases, only very slightly, so that the energy confinement time actually increases with the additional power, see Fig. 5. In these shots H_{RLW} reaches a value of 4 with central temperatures above 10keV. Figure 6 shows the χ_e profiles for such a shot.

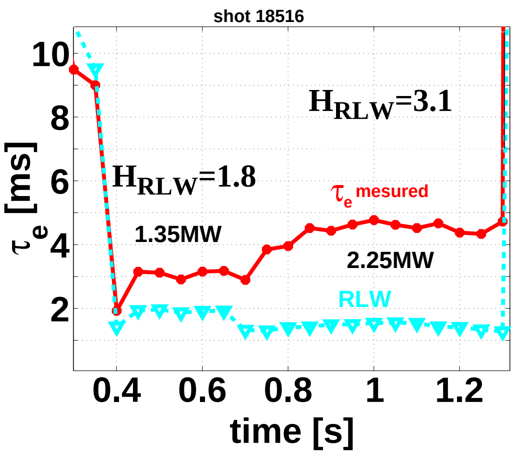


Figure 5. Electron energy confinement time for a shot with low χ_e "prepared" in the plasma centre by ECRH beams at ρ=0.4 at 0.4-0.7s

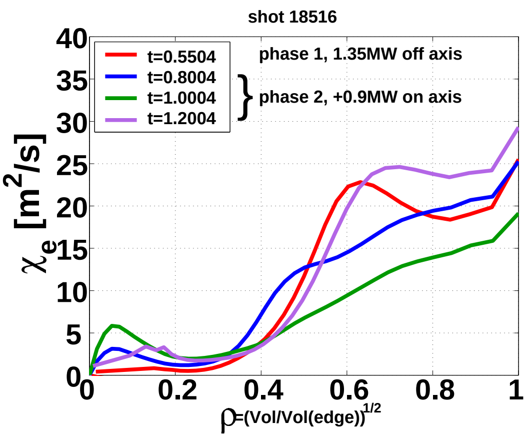


Figure 6. χ_e profiles for the shot of Fig. 5 calculated from T_e and n_e experimental profiles using the formula

$$\chi_e = \frac{-Q_e}{n_e \cdot \nabla T_e}$$

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1. Z.A.Pietrzyk, C.Angioni et al. Physics of Plasma July 2000