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Abstract

Current profile tailoring by Electron Cyclotron Heating (ECH) and Current Drive (ECCD) is used to improve core electron energy confinement in TCV. Counter-ECCD on-axis alone achieves this goal in a transient manner only. A stable scenario is obtained by a two-step sequence of off-axis ECH, which stabilizes MHD modes, and on-axis counter-ECCD, which generates a flat or inverted current profile. This high-confinement regime, with central temperatures up to 9 keV, has been sustained for the entire duration of the heating pulse, or over 200 energy confinement times.

52.55.Fa, 52.50.Gj, 52.25.Fi

The heat transfer coefficients in the conventional mode of operation of a tokamak plasma discharge (known as L-mode) are orders of magnitude higher than those attributable to Coulomb collisions. The quest for fusion energy has been constantly accompanied by a search for ways to reduce this anomalous transport and improve energy confinement [1]. The first and best-known regime of improved tokamak confinement and performance is the H-mode [2], in which a transport barrier is created near the plasma edge. More recently, enhanced confinement has been obtained by generating an Internal Transport Barrier (ITB) in the plasma [3]. It has been observed that ITBs are formed when the current profile is hollow or very flat [4]. Such a profile can be created with intense central heating during current ramp-up [5]; however, this scenario is intrinsically transient.

Localized heating or current drive can modify the current profile at constant total current in quasi-steady state, i.e. for a period exceeding the longest system time scale, represented by the current redistribution time. Electron Cyclotron Heating (ECH) and Current Drive (ECCD) are ideally suited for this application, as power is deposited in a narrow region which can be accurately and easily chosen by external means. The heating effect raises the local temperature, hence the conductivity and the current density; additional current drive can be applied in either direction, enhancing (co-ECCD) or opposing (counter-ECCD) this effect. With optimal power deposition the heat transfer coefficient can be reduced over a significant fraction of the plasma core rather than in a narrow "barrier" region. The physical mechanisms giving rise to these two scenarios can be rather different, although the term ITB has been used in the literature to describe both [6]. In this Letter we report on the observation of the former type of regime, which we denote by Improved Central Confinement (ICC) for clarity.

TCV (Tokamak à Configuration Variable) is a medium-sized tokamak (R=0.88 m, a=0.25 m, B_ϕ=1.45 T, $I_p \leq 1$ MA), with an elongated (κ=3) vacuum vessel compatible with a wide variety of plasma shapes [7]. Up to six 82.7-GHz gyrotrons were employed in this experiment, each connected to an independent transmission line and launcher delivering on average 0.45 MW EC power (for a total of 2.7 MW) to the plasma at the second harmonic in X-mode.

Steerable mirrors provide maximum flexibility for changing the power deposition location during a shot.

A straightforward technique for the generation of a hollow or flat current profile is counter-ECCD in the plasma center, provided that the non-inductive current decrease is larger than the inductive increase due to the enhanced conductivity. This scenario has been previously produced in TCV and resulted in significantly higher confinement than with central ECH or co-ECCD [8]. In this study it was found that core sawtooth oscillations were inhibited as the central safety factor q rose above 1. With the aid of numerical transport simulations, it was concluded that the improvement in confinement could be attributed solely to the avoidance of the sawtooth instability. However, this regime is often unstable, owing to the appearance of MHD modes that lead to sudden performance deterioration or even a disruption [8].

We have now developed a stable path to ICC, which results in confinement equal to or better than that of the regime described above. The route to stable ICC begins with localized off-axis ECH, which produces broader temperature and pressure profiles than Ohmic heating only, with lower heat diffusivity and correspondingly higher temperature in the center. The broader temperature profile in turn generates a broader, which is favorable with respect to MHD instabilities. In a second phase, once current relaxation is complete, additional power is applied near the plasma center, resulting in higher temperature and high total plasma energy. The enhanced confinement is experimentally found to depend upon the centrally deposited beams possessing a counter-ECCD component, possibly generating a q profile with negative central shear. The improved stability of the broad target current profile is carried over to this second phase, which can then be maintained without deterioration.

In Fig. 1 the temperature and density profiles are shown for three discharges using the scenario described above. In all cases the central power is 0.9 MW and is applied 300 ms after the off-axis heating. The green and blue curves differ in the form of the on-axis EC power: pure ECH for the former and counter-ECCD for the latter; the ECH power deposited off-axis is 0.9 MW in both cases. Clearly, counter-ECCD in the center leads to a better plasma performance. The case shown in red is similar to the one in blue, except that the initial off-axis power in the former is 1.35 MW. At this power the performance is improved further and the plasma appears to be equally stable. In the rest of this Letter we shall focus on the scenario described by the blue curves. Some of the key parameters for these shots are: elongation κ=1.6–1.7, triangularity δ=0.2–0.22, edge safety factor $q_{\rm edge}$=7–7.5, and total plasma current I_p=200 kA.

An important reference confinement time is that given by the Rebut-Lallia-Watkins (RLW) scaling [9], which is expected to be appropriate for hot-electron, cold-ion regimes such as those of TCV at the densities used in this study (line-averaged density $\sim 1.5 \times 10^{19}$ m^{-3}, ion temperature typically 10 to 20 times lower than the electron temperature), and is indeed in agreement with experiment in Ohmic and often in L-mode conditions [10]. We can thus characterize the confinement enhancement in the present study by the ratio $\mathrm{H}_{\mathrm{RLW}}$ of the measured confinement time to that predicted by the RLW model. Figure 2 shows the central temperature and $\mathrm{H}_{\mathrm{RLW}}$ for one discharge with on-axis ECH and two discharges with on-axis counter-ECCD; the latter two differ only slightly in the heating locations (normalized minor radii 0.35 and 0.1 for the first one versus 0.30 and 0.0 for the second one). It is clear that counter-ECCD is essential for reaching the best confinement, with $\mathrm{H}_{\mathrm{RLW}} > 3$ and a central temperature of $\sim$9 keV. Here, the ICC regime is maintained throughout the duration of the second EC pulse, equal to 1.1 s or about 200 energy confinement times. No low-frequency MHD modes were observed by magnetic probes in these discharges. It is important to note that the two ICC cases have similar confinement properties, even though the former shows sawtooth activity (most likely due to the slightly off-axis counter-ECCD deposition), with up to 3 keV temperature drop during a sawtooth crash, whereas the latter does not.

The stability of this regime is very sensitive to the off-axis power deposition locations. Increasing the distance of the heating location from the axis results in a larger improved confinement region, but also in increased temperature perturbations by MHD modes, sawteeth, and occasionally even disruptions. In addition, a delay between the off-axis and on-axis heating phases is also necessary for the stability of the ultimate ICC regime: this delay is of the order of the current redistribution time, ~200 ms in these cases. This is shown in Fig. 3, in a comparison between the reference stable ICC case shown previously, a similar shot with off-axis ECH and on-axis counter-ECCD but applied at the same time, and a shot with all counter-ECCD on axis and no off-axis heating. The central temperature in the second case undergoes violent oscillations, whereas in the third case the plasma disrupts after 450 ms.

To further elucidate the origin of the enhanced confinement, it is useful to calculate the local heat diffusivity χ_e. This can be done from the temperature and density profiles measured by Thomson scattering and from the EC power deposition profile supplied by the TORAY ray-tracing code [11], assuming that the heat transport is dominated by diffusion processes. In all cases with improved confinement χ_e is 3-5 times below the Ohmic level in the central part of the plasma ($\rho < 0.25$) during the initial off-axis heating phase; in the later on-axis counter-ECCD phase χ_e increases as a consequence of the additional power, but still does not exceed the Ohmic level.

Our goal in this experiment was to explore the possibility that core electron confinement could be improved by flattening or reversing the gradient of the current profile in the central part of the plasma, a condition which is known to be conducive to the formation of transport barriers in the ion channel [3,4]. As was remarked earlier, unlike our earlier transient ICC regime [8], these stable ICC regimes cannot be explained by the inhibition of sawtooth oscillations. Cases both with and without sawteeth have been observed, depending on the off-axis heating and on-axis counter-ECCD locations, with comparable central temperatures (up to 9 keV) and global confinement.

The current profile is not directly measured but is reconstructed by the PRETOR code [12]. Even though PRETOR is primarily a transport code, it can be used as a fixed-boundary equilibrium solver [13] constrained by the experimental density and temperature profiles, effective ion charge Z_{eff}, and edge loop voltage, and by the power deposition and EC-driven current profiles provided by TORAY [14]. The calculated safety factor, however, has a large uncertainty in the core which reflects the high sensitivity of the calculation to the amount and location of the counter-ECCD component (which is also affected by the off-axis beams through density profile modification). Within the error bar, represented by the shaded area in Fig. 4(b) for the ICC phase of a discharge, the q shear can be either zero or negative in the center.

The evolution of the temperature and current profiles can be simulated by PRETOR in "predictive" mode [13], i.e. used as a transport code with the local RLW heat transfer coefficients. A large q shear (positive or negative) leads to low diffusivities in this model. As shown in Fig. 4(a), the simulation is able to reproduce the experimental temperature profiles with good accuracy in all the relevant phases of the discharge. Within the framework of this model, a steep q gradient in the core is essential for ICC formation. The predicted q profile indeed exhibits a nonzero, and negative, central derivative, as seen in Fig. 4(b). In the PRETOR simulations, both the q profile near the center and the value of the central temperature are very sensitive to the position of the counter-ECCD component, the highest temperature being obtained with exact on-axis deposition. An experimental scan of the counter-ECCD deposition radius was carried out to test this prediction: it was observed that a displacement equal to only 10% of the minor radius caused a 40% variation in the central plasma temperature, in qualitative agreement with the PRETOR predictions.

In conclusion, Improved Central Confinement has been achieved in quasi-steady-state operation in a hot-electron, cold-ion plasma without significant MHD activity. The scenario described here can be extended in principle to steady-state tokamak operation, as it does not depend on current ramp-up. The improved confinement can be obtained in shots both with and without sawteeth; thus, confinement enhancement is not attributable to sawtooth stabilization for these discharges. Transport simulations are capable of reproducing the experimental results in a majority of cases, using local RLW transport coefficients, and show that the magnetic shear in the core can be negative in this regime.

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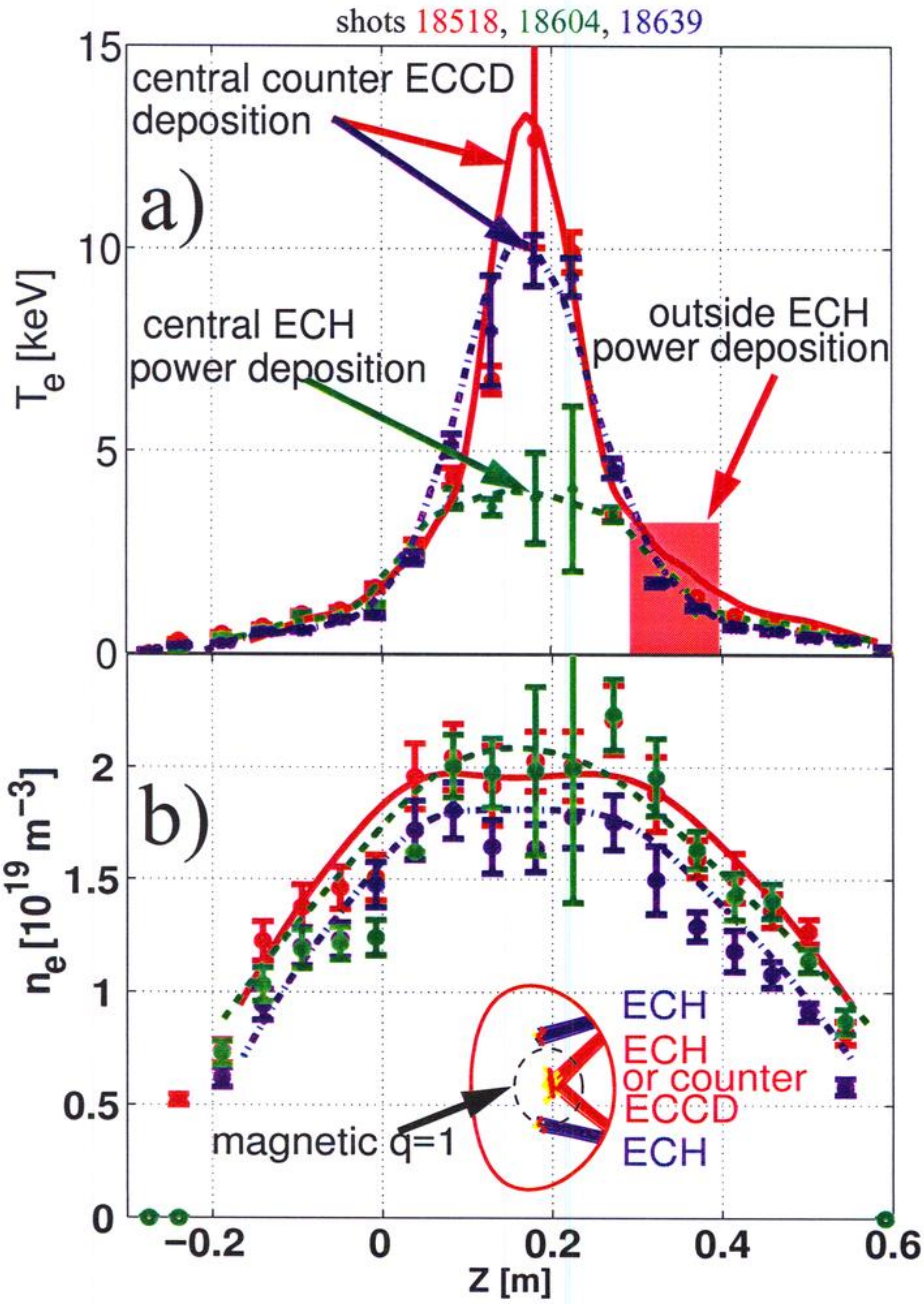

FIG. 1. (color) {(a) Electron temperature and (b) density profiles measured by Thomson scattering along a vertical chord, for three shots with off-axis heating (at a normalized minor radius $\rho_h = 0.37$) augmented300 ms later by on-axis heating. Dashed green curves: 1.35 MW off-axis ECH and 0.9 MW on-axis ECH; dash-dot blue curves: 0.9 MW off-axis ECH and 0.9 MW on-axis counter-ECCD; solid red curves: 1.35 MW off-axis ECH and 0.9 MW on-axis counter-ECCD.

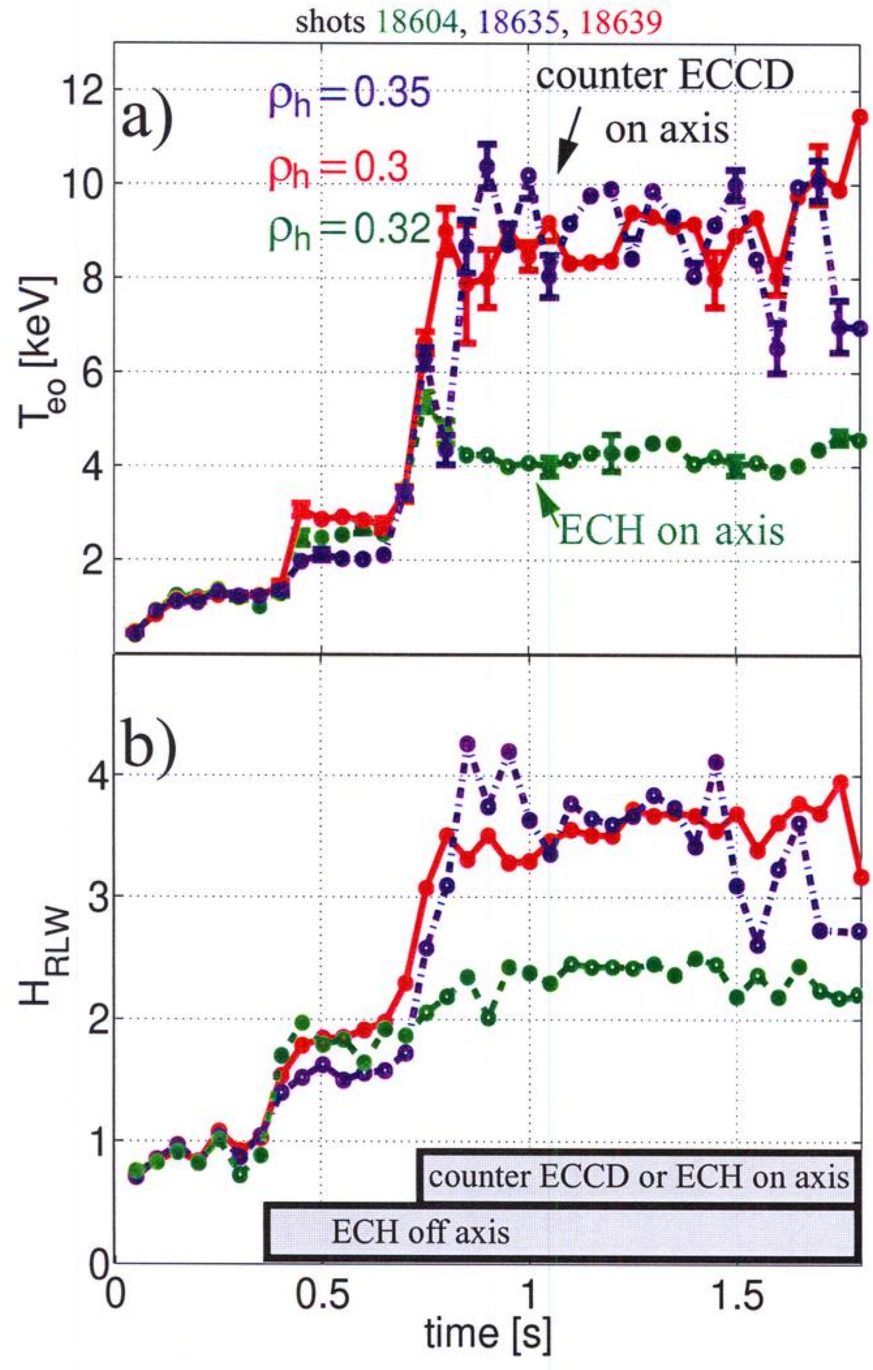

FIG. 2. (color) Time histories of a) central electron temperature and b) enhancement factor over RLW energy confinement time, for three discharges with 0.9 MW off-axis ECH (normalized minor radius of power deposition given by ρ_h), augmented after 300 ms by 0.9 MW on axis (ECH for dashed green curves, counter-ECCD for solid red and dash-dot blue curves). The insert indicates the time dependence of the EC power delivered to the plasma.

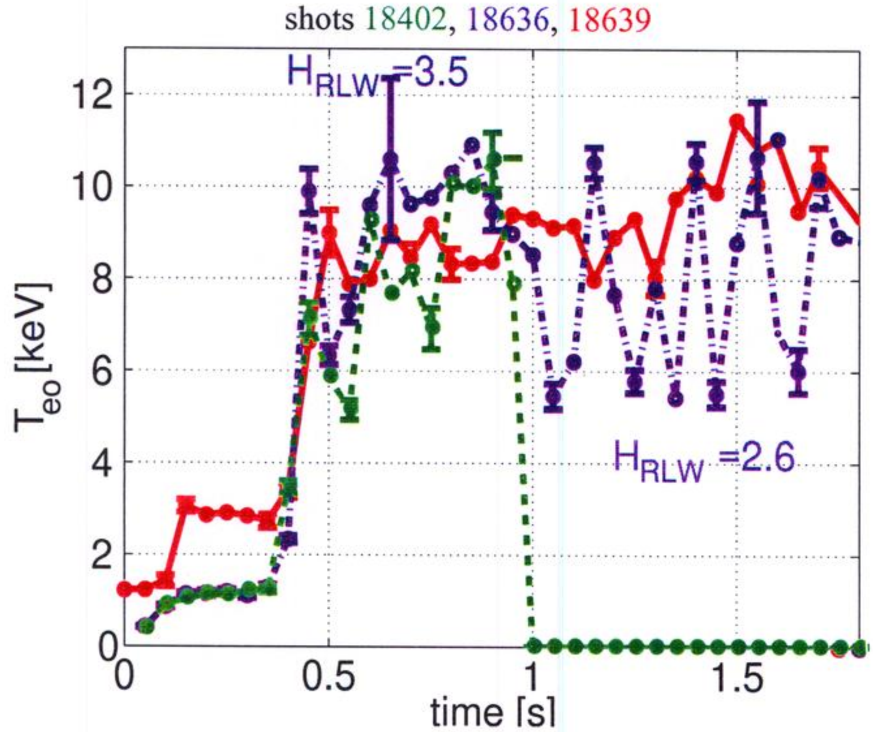

FIG. 3. (color) Central electron temperature vs. time for three discharges: 0.9 MW off-axis ECH augmented 300 ms later by 0.9 MW on-axis counter-ECCD [as in Fig.\ \ref{figure2}(b) shifted in time by -300ms], solid red curve; 0.9 MW off-axis ECH and 0.9 MW on-axis counter-ECCD applied at the same time, dash-dot blue curve; 2.7 MW on-axis counter-ECCD only, dashed green curve.

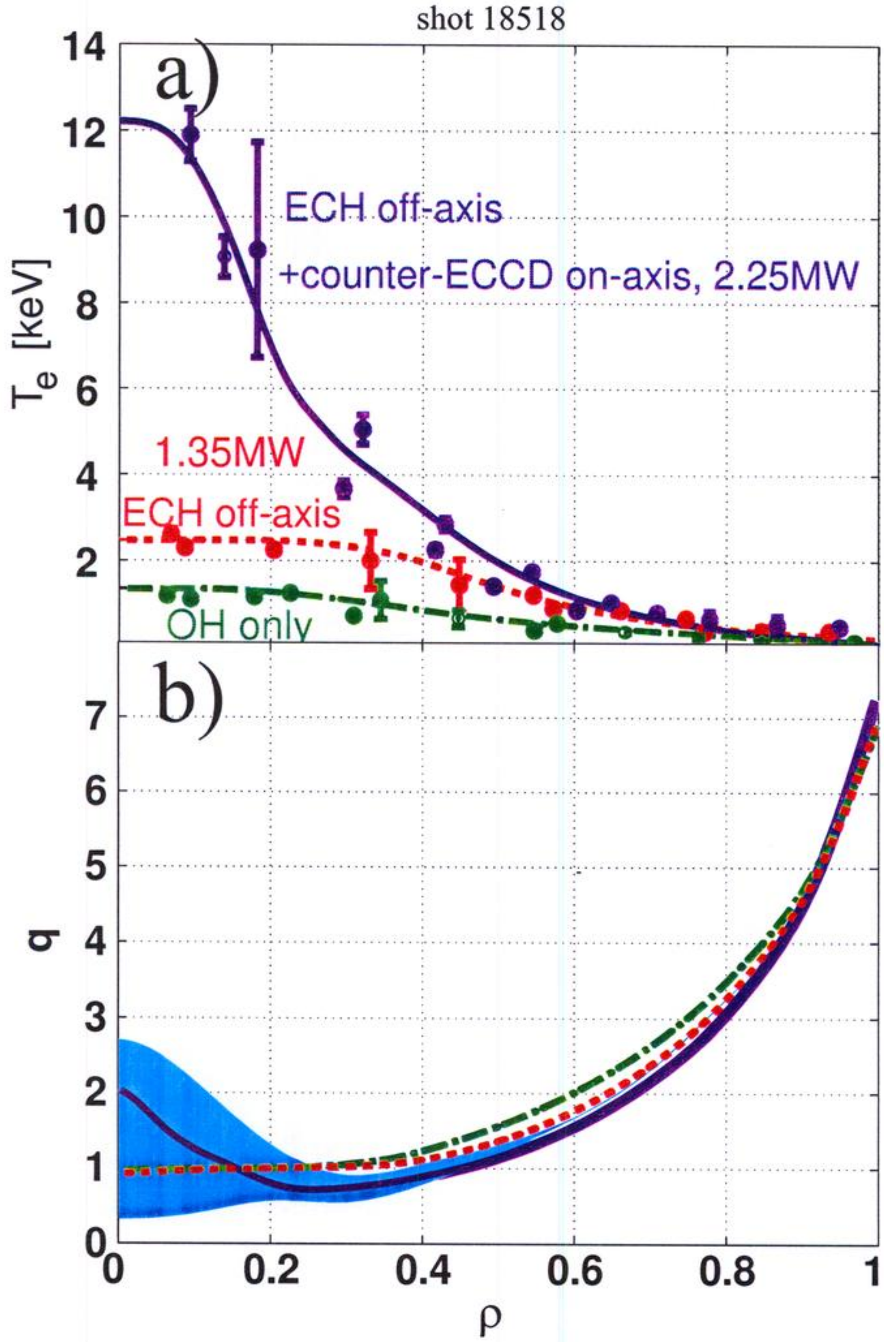

FIG 4. (color) a) Electron temperature profiles calculated by PRETOR in 3 different phases (green: Ohmic, red: off-axis ECH, blue: ICC) of a discharge from Fig.1, with experimental measurements by Thomson scattering shown for comparison; b) corresponding safety factor profiles from the same calculation. The shaded area in (b) represents the uncertainty in the determination of the q profile by PRETOR in "diagnostic" mode, primarily due to uncertainties in the location and magnitude of the central counter-ECCD component.