Particle Pinch with Fully Noninductive Lower Hybrid Current Drive in Tore Supra

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Recently, plasmas exceeding 4 min have been obtained with lower hybrid current drive (LHCD) in Tore Supra. These LHCD plasmas extend for over 80 times the resistive current diffusion time with zero loop voltage. Under such unique conditions the neoclassical particle pinch driven by the toroidal electric field vanishes. Nevertheless, the density profile remains peaked for more than 4 min. For the first time, the existence of an inward particle pinch in steady-state plasma without toroidal electric field, much larger than the value predicted by the collisional neoclassical theory, is experimentally demonstrated.

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Particle transport is a subject of utmost importance in fusion plasmas. A peaked density profile is attractive for (i) improving the fusion rate which is proportional to the square of the density and (ii) increasing the plasma pressure gradient, which is favorable for a large bootstrap fraction in advanced tokamak operation. However, a peaked density profile leads to an accumulation of impurities in the case of collisional transport, which increases the radiation losses and decreases the fuel concentration. It is described by the expression relating the particle flux (Γ) and the density profile (n_e): $\Gamma = -D \cdot \nabla n_e + V \cdot n_e$, where D and V are, respectively, the diffusion coefficient and pinch velocity. Concerning V, many theoretical works predict the existence of an anomalous particle pinch. Some call for density profiles related to the temperature profile, others related to the safety factor profile [1–4]. Experiments at JET [5] and ASDEX [6] tokamaks, with neutral beam injection and finely tuned gas puffing, show a particle pinch velocity close to the neoclassical prediction. The neoclassical pinch ($V_{\rm neo}$) is mainly driven by the toroidal electric field (E_φ), the so-called Ware pinch [7]. In Ohmic discharges of the TCV tokamak [8] and in L and H modes in the DIII-D tokamak [9], the peakedness of the density profile was found to be larger than that expected with the Ware pinch alone, as well as in L-mode plasmas heated by radio frequency waves at JET [10]. In these experiments, E_φ still persists; therefore, the contribution of the Ware pinch could not be eliminated. In contrast, the full noninductive current drive Tore Supra plasmas offer the opportunity to study this phenomenon in a clear situation.

In Tore Supra, discharges have been obtained with zero loop voltage during more than 3 min [11]. The plasma current is fully driven by lower hybrid waves (LHCD) over a time much longer than the current diffusion time. Therefore, the toroidal electric field is absent over the whole plasma volume. In these unique conditions, the density profile is found to be significantly peaked, in spite of negligible central particle source. The neoclassical Ware pinch velocity cannot be invoked to explain this very stable resilient peaking.

The recent LHCD deuterium discharges were performed at plasma current $I_p = 0.5$–0.7 MA, toroidal field $B = 4$ T, major radius $R = 2.4$ m, minor radius $a = 0.71$ m, central density $n_e(0) = 2$–3.5×10^{19} m^{-3}, central electron temperature $T_e(0) = 4.8$ keV, and central ion temperature $T_i(0) = 1.3$ keV. These experiments were carried out in the new configuration of Tore Supra with a toroidal pump limiter [12]. A typical full LHCD plasma is illustrated in Fig. 1. The plasma density is well controlled over 4 min [Fig. 1(b)]. Interpretative analysis of this discharge has been performed using the integrated modeling CRONOS code [13]. The LH driven current profile is assumed to have the same shape as the fast electron bremsstrahlung profile measured by a hard x-ray tomographic system [14]. The LH current is mostly the total current, since the bootstrap fraction is less than 10%. The results given by CRONOS are in good agreement with the time evolution of global parameters relating to the current diffusion (e.g., loop voltage, self-inductance) and thus confidently provide the profile of E_φ. As shown in Fig. 1(c), a null toroidal electric field was maintained for about 3 min in discharge No. 30414. Its associated Ware pinch is the dominant part of the neoclassical pinch velocity $V_{\rm neo}$, as shown in Fig. 2(a) displaying the $V_{\rm neo}$ profiles with $E_\varphi \approx 4 \times 10^{-2}$ V/m (Ohmic plasma) and without E_φ. Here, $V_{\rm neo}$ is computed by the integrated module NCLASS [15] of the CRONOS package. It contains all neoclassical effects, including the inward/outward pinch driven by the temperature and density gradients of all particle species. Although $V_{\rm neo} \approx 0$, the peaking factor of n_e profile, $n_e(0)/\langle n_e\rangle$ deduced from interferometry measurements, was found to be around 1.8 [Fig. 1(d)]. The radial density profile during the LHCD phase ($t = 10$–250 s) normalized to the Ohmic value (at $t = 4.8$ s), measured by Thomson scattering diagnostic, is displayed in Fig. 2(b). The main difference appears for $r/a > 0.6$. The modification of the profile in the peripheral region can be mainly attributed to a change

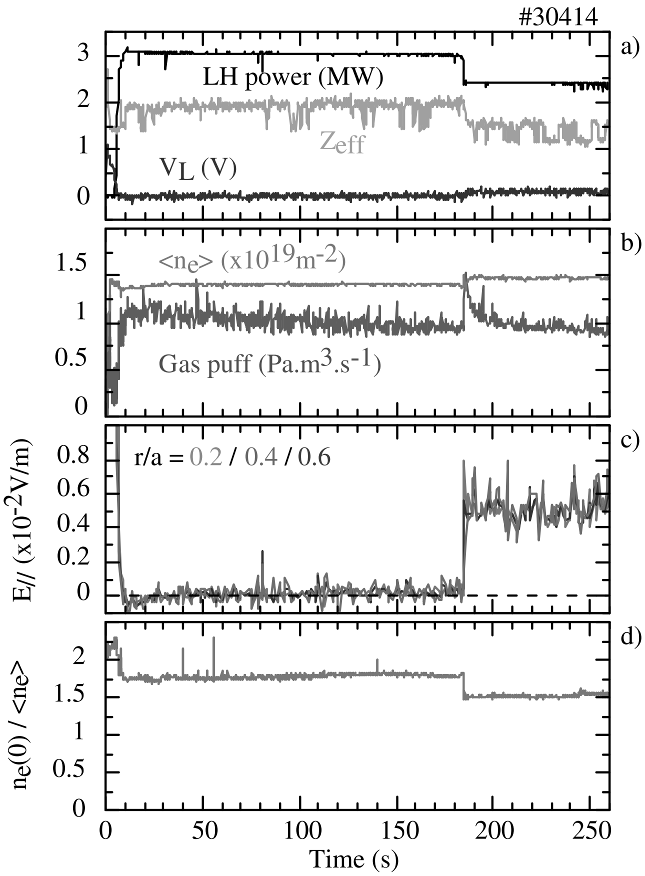

FIG. 1. Time evolution of full LHCD discharge, No. 30414: (a) lower hybrid power, effective charge, and loop voltage; (b) volume averaged density and gas fueling; (c) toroidal electric field, at various normalized radius ($r/a = 0.2$, 0.4, 0.6), given by CRONOS; (d) density profile peaking factor, $n_e(0)/\langle n_e \rangle$, from interferometry diagnostic.

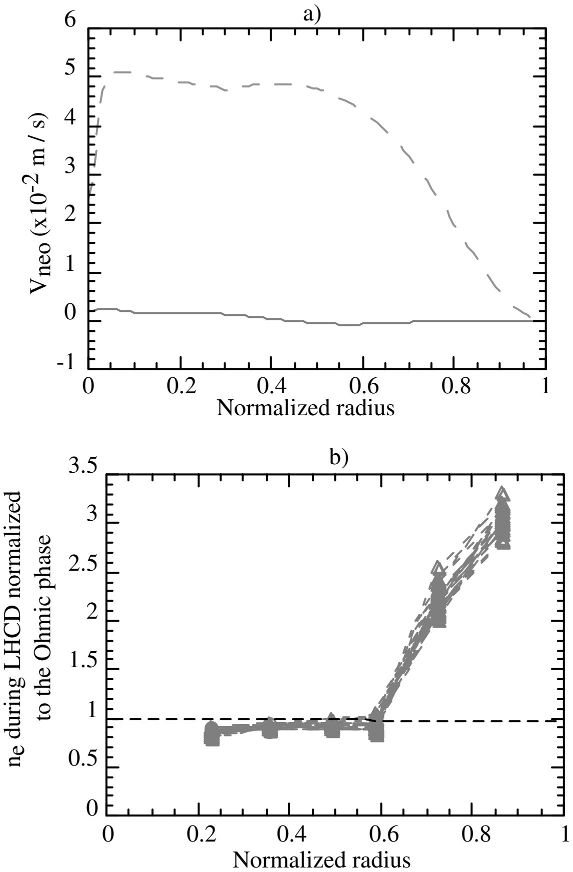

FIG. 2. Discharge No. 30414. Radial profile of (a) Neoclassical pinch velocity from NCLASS. Full line: LHCD phase (at $t = 170$ s); dashed line: Ohmic phase (at $t = 4.8$ s), (b) Density during the full LHCD phase (for $10 \text{ s} \leq t \leq 250$ s) normalized to the Ohmic phase (at $t = 4.8$ s), from 6 channels of Thomson scattering diagnostic.

of the recycling and/or an increase of impurity with the application of LHCD. In constrast, in the gradient region ($0.2 \leq r/a \leq 0.6$), this ratio is almost constant and close to 1, indicating that the n_e profile during the LHCD phase has the same shape as that during the Ohmic phase although E_φ vanishes. The ionization source due to intrinsic impurities was evaluated by mass spectrometer measurements. Carbon and oxygen, approximately the same concentration, were dominant impurities. Their densities are evaluated consistently with the measurements of Z_{eff}, $T_i(0)$ and the neutron rate. Effective charge Z_{eff} increased from the Ohmic level of 1.5 to about 2 [Fig. 1(a)]. As shown in Fig. 3(a), the contribution of these central impurities to the electron density is found to be negligible inside $r/a = 0.6$. In this figure, the impurity electron source is certainly overestimated, since we assume that C and O are fully ionized inside $r/a = 0.6$, while C and O are completely ionized in the edge low T_e region. The main particle sources from the recycling on the toroidal pump limiter and the external gas puffing [5×10^{20} particle $\cdot$ m^{-3} $\cdot$ s^{-1}, Fig. 1(b)] have been evaluated with the 3D neutral code EIRENE [16]. The radial profile of these sources is shown in Fig. 3(b). This indicates that a negligible fraction, less than 1% of total ionized deuterium, is located inside $r/a = 0.7$. Therefore, the peaked profile inside the core region ($r/a \leq 0.6$) during LHCD is linked to particle transport properties. In this case, the ratio V/D is determined by the inverse of the density gradient length $L_n = n_e/\nabla n_e$. For a similar 1 min discharge fully driven by LHCD (No. 30428), with good spatial resolution of the n_e profile [Fig. 4(a)] measured by reflectometry [17], the radial profile of $1/L_n$ indicates that V/D is almost constant and equal to 1 m^{-1} in the gradient region, $r/a = 0.3$–0.6 [Fig. 4(b)].

To characterize V at the plasma periphery, 1D modeling is required. The model in Ref. [18] takes into account the parallel particle sink in the scrape off layer and describes accurately the outer part of the discharge. The D profile is assumed to be the one found in previous studies of Ohmic discharges with similar geometry and density [19], consistent with the particle confinement time $\tau_P \approx 0.13$ s obtained in gas modulation experiments. As shown

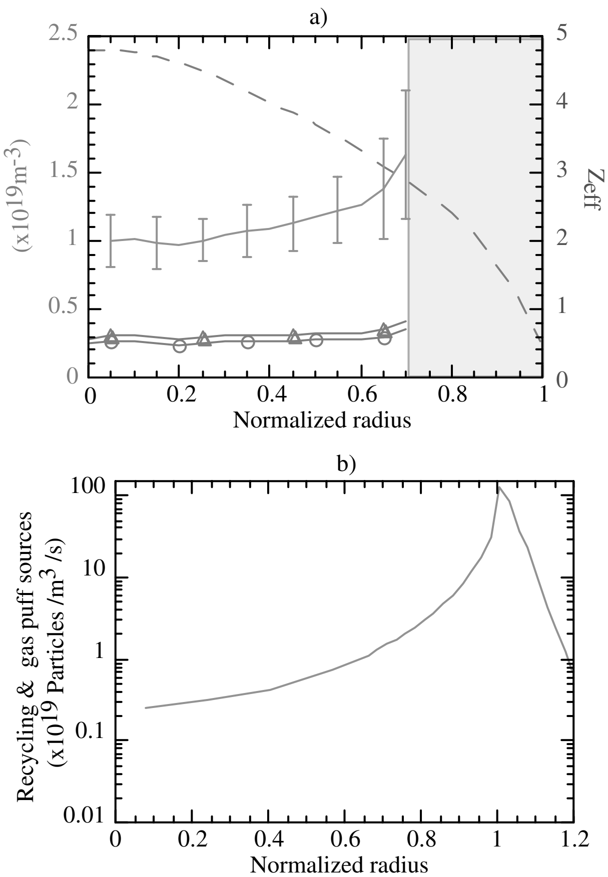

FIG. 3. Discharge No. 30414. Radial profile of (a) electron density (dashed line), carbon density (full line/triangles, multiplied by 10), oxygen density (full line/circles, mutiplied by 10) and measured $Z_{\rm eff}$ (full line); (b) ionization source from the recycling on the toroidal pump limiter and the external gas puffing, computed with the 3D EIRENE code.

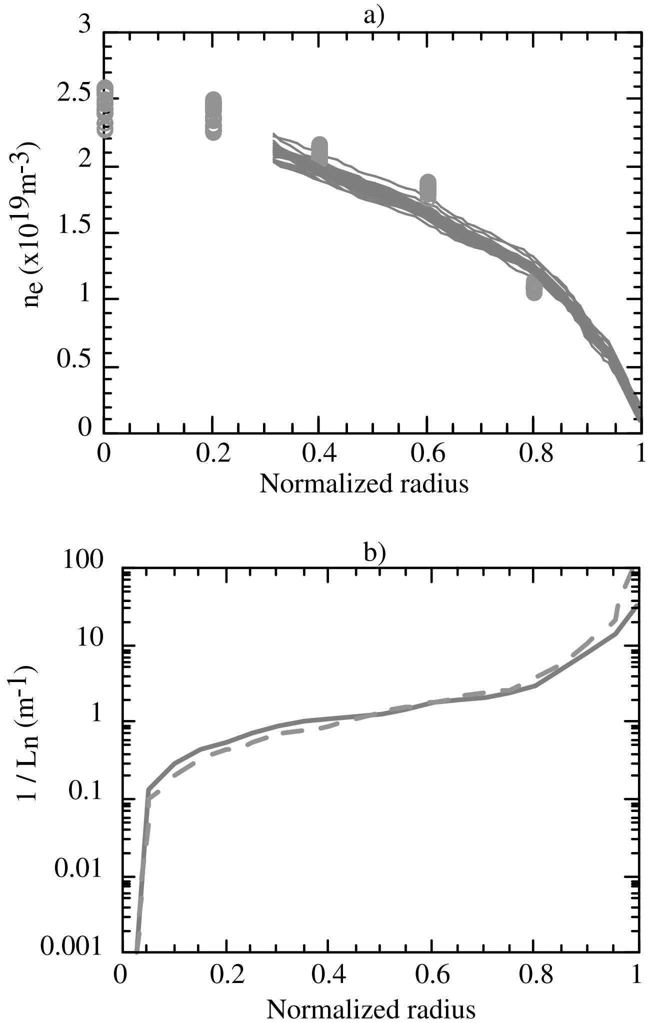

FIG. 4. Radial profile of a 1 min discharge fully driven by LHCD (No. 30428): (a) density measured by reflectometry (full lines) and interferometry (circles) diagnostics; 29 time slices from 3–64 s (LHCD phase from 5to 62 s). (b) Inverse of density gradient length (full line: LHCD phase, at $t = 30$ s; dashed line: Ohmic phase, at $t = 3.2$ s).

in Fig. 5(a), the simulation well reproduces the measured n_e profile of discharge No. 30428 mentioned above. To simulate the peaked profile, we must use a value of V 2 orders of magnitude higher than $V_{\rm neo}$ in the gradient region and up to 10 m/s at the plasma periphery, as shown in Fig. 5(b). Since the particle confinement time $\tau_{\rm P}$ was found to vary as $P^{-0.2}$ in previous work [20], D and therefore V should be underestimated with application of 3 MW LHCD (compared to 0.6 MW of Ohmic power). However, the agreement between the increase of the recycling flux (measured by the H_α emission on the toroidal pump limiter) and the increase of the parallel particle sink (expected from the edge temperature/density) suggests that there is no major modification of the particle source with the application of LH power. In consequence, the profile of V shown in Fig. 5(b) is probably realistic. To evaluate the uncertainty on the $V_{\rm neo}$ profile shown in Fig. 5(b), we have run NCLASS with artificially increased effective charge: $Z_{\rm eff} = 6$ (instead of 2), and taking into account only iron as an impurity. In spite of this overestimation, $V_{\rm neo}$ remains 2 orders of magnitude below the pinch velocity [Fig. 5(b)]. Of course, the same simulated density profile could be obtained when using V around $V_{\rm neo}$ [1×10^{-3} m/s, in Fig. 5(b)]. But in this case, we would need a diffusion coefficient $D = 1 \times 10^{-3}$ m^2/s, slightly lower than the collisional value $D_{\rm neo} = 2 \times 10^{-3}$ m^2/s given by NCLASS. The corresponding $\tau_{\rm P}$ would be around 16 s, much higher than the experimental value. Consequently, the possibility for fully neoclassical particle transport in these plasmas is ruled out. Note that the LH waves, in the present case, can modify the neoclassical pinch velocity, as suggested in Ref. [21].

In summary, peaked density profiles have been observed in Tore Supra discharges with full LHCD (zero loop voltage) and negligible central particle source for up to 4 min. Such a peaked profile can be explained only by a particle pinch velocity 2 orders of magnitude above the

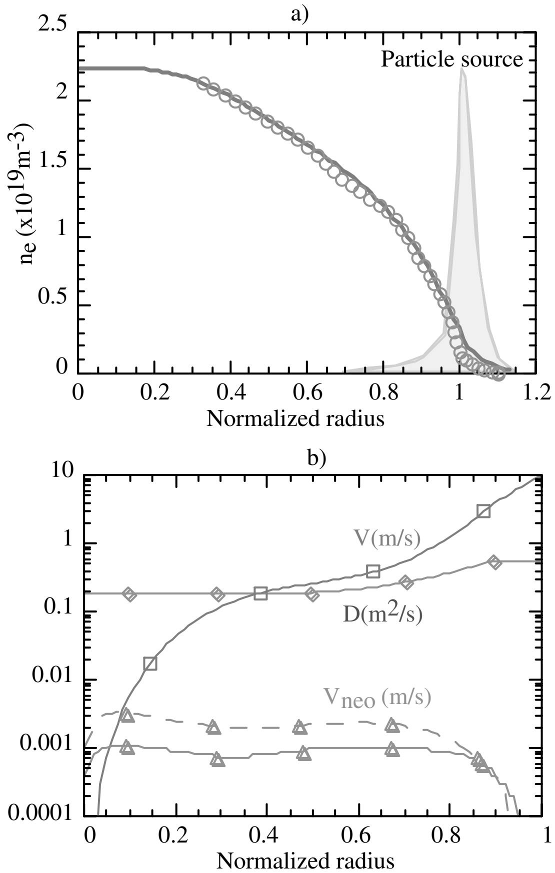

FIG. 5. 1D simulation of discharge No. 30428, at $t = 30$ s: (a) density profile (line: simulation; circles: reflectometry measurements); (b) pinch velocity (squares) and diffusion coefficient (diamonds) used to reproduce measured density profile, $V_{\rm neo}$ given by NCLASS (triangles), $V_{\rm neo}$ when assuming $Z_{\rm eff} = 6$ instead of 2 and iron impurity only (dashed line/triangles).

neoclassical value given by NCLASS. The ratio V/D, determined by the measurement of the density gradient length, is found to be close to 1 m^{-1} in the gradient region. The parametric dependence of D and V has yet to be studied in order to discriminate among the different theoretical predictions. Taking advantage of the long duration Tore Supra plasmas with zero loop voltage, we are expecting to learn more on this crucial issue for the International Thermonuclear Experimental Reactor prediction of particle transport.

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