Steady-State Fully Noninductive Current Driven by Electron Cyclotron Waves in a Magnetically Confined Plasma

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(Received 29 November 1999)

A steady-state, fully noninductive plasma current has been sustained for the first time in a tokamak using electron cyclotron current drive only. In this discharge, 123 kA of current have been sustained for the entire gyrotron pulse duration of 2 s. Careful distribution across the plasma minor radius of the power deposited from three 0.5-MW gyrotrons was essential for reaching steady-state conditions. With central current drive, up to 153 kA of current have been fully replaced transiently for 100 ms. The noninductive scenario is confirmed by the ability to recharge the Ohmic transformer. The dependence of the current drive efficiency on the minor radius is also demonstrated.

PACS numbers: 52.50.Gj, 52.35.Hr, 52.55.Fa

The study of magnetically confined plasmas in toroidal configurations constitutes one of the major lines of research in controlled thermonuclear fusion. In such configurations, plasma confinement is ensured primarily by a toroidal current circulating in the plasma. In tokamaks, the simplest and most widely used technique to produce this current uses induction by a time-varying magnetic flux; the resulting "Ohmic" plasma discharge is thus inherently pulsed. The desire for a steady-state device has motivated the development of alternative current-drive methods in the past two decades. Prominent among these are methods that utilize injected electromagnetic waves.

Steady-state or long-pulse scenarios with full current replacement using lower-hybrid current drive (LHCD) have been achieved in many tokamaks since the PLT steady-state results [1] and since the recharging of the Ohmic transformer was demonstrated in ASDEX [2]. The potential for similar experiments using electron cyclotron current drive (ECCD) has long been known, but only recently have advances in gyrotron source technology permitted the realization of steady-state scenarios by combining ECCD with LHCD [3], as well as full current replacement in a transient manner by ECCD alone [4]. In this Letter, we present the first demonstration of fully noninductive current drive in stationary state for 1.9 s at 123 kA and line-averaged density $n_{\mathrm{el}} \approx 10^{19}$ m^3, as well as transient current replacement for 0.1 s at 153 kA and central density $n_{e0} = 1.75 \times 10^{19}$ m^{-3}, with 1.5 MW of injected power.

In addition to steady-state operation, an important benefit of ECCD is profile control. It has become increasingly clear during the last decade that reactorlike tokamaks will require profile control in order to operate close to density and β limits. In addition, advanced steady-state scenarios currently under study also depend on pressure and current profile control, both of which are effectively realized with EC waves because of their localized single-pass absorption.

The TCV tokamak has a highly elongated vacuum vessel and can generate a wide variety of plasma shapes [5]. The EC system, presently comprising three 0.5 MW gyrotrons, is very flexible in that the three poloidal injection angles can be independently controlled during the discharge, spanning a range of about 50°, and the toroidal angles can be modified between discharges from about $-50°$ to $+50°$ as projected on the plasma midplane [6]. The polarization of each gyrotron can also be varied, but only results obtained with more than 97% X-mode-like coupling are presented here. The frequency is at the second harmonic, 82.7 GHz, and the maximum pulse length is 2 s. The plasma geometry used for most of the discharges in this study is $R_0 = 0.88$ m, $a = 0.25$ m, $B_0 = 1.43$ T, $\kappa \approx 1.5$, $q_a \approx 10$, limited on the inner wall of the vacuum vessel.

Preliminary results from a scan of the toroidal angle φ have shown that the optimum angle for current drive is large, around 35° from perpendicular [7], and we have used $\varphi = 35°$ in all the experiments presented here. First, we show in Fig. 1 that we can clearly recharge the Ohmic transformer if the feedback reference value of the total plasma current I_p is set to a lower value than the noninductively driven current. In this case, only two gyrotrons (total 1 MW) were used; the beams were aimed at the plasma center to maximize the current driven, which is proportional to the local plasma temperature. A steady recharging rate of about 1 kA/s is demonstrated with $I_p = 80$ kA, $n_{e0} \approx 1.9 \times 10^{19}$ m^{-3}, for a period of over 1.5 s, far exceeding the current redistribution time of the plasma. The estimated noninductive current is about 100 kA, corresponding to a current drive efficiency

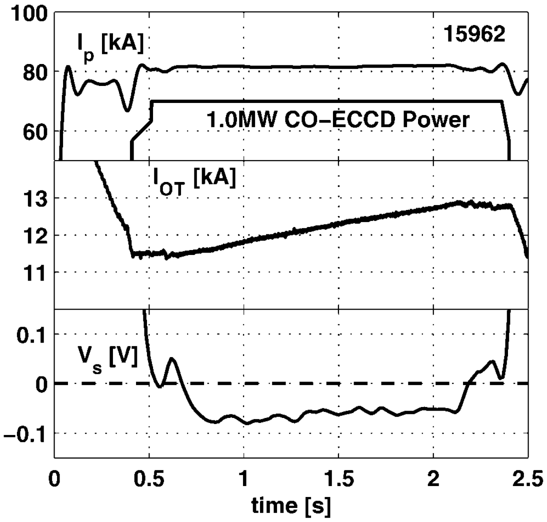

FIG. 1. Recharging of the Ohmic transformer for 1.5 s with 2 gyrotrons (1 MW total) aiming at the plasma center. The plasma current I_p, the current in the Ohmic transformer I_{OT}, and the surface loop voltage V_s are shown. In this case, $I_p = 80$ kA, $n_{\mathrm{el}} \approx 1.3 \times 10^{19}$ m^{-3}, $n_{e0} \approx 1.9 \times 10^{19}$ m^{-3}, $T_{e0} \approx 3.5$ keV. Note that $V_s = 0.8$ V before ECCD is turned on.

$\eta_{20\mathrm{CD}} = R\, n_e\, I/P \approx 0.017$ (10^{20} A/W m^2). Since the Ohmic current fraction is difficult to estimate, an accurate measurement of the driven current requires the plasma current reference to be set such that the Ohmic fraction is zero. This is shown in Fig. 2. We have obtained zero loop voltage for about 100 ms from 0.5 s, with $I_p = 153$ kA, $n_{e0} \approx 1.75 \times 10^{19}$ m^{-3}, $T_{e0} = 4 \pm 0.8$ keV, and $Z_{\mathrm{eff}} \approx 5$ (due to the high power in a low density limiter discharge), with the three gyrotrons aiming near the plasma center. This yields a current drive efficiency of about $\eta_{20\mathrm{CD}} \approx 0.013$ after substraction of $\sim$20% of bootstrap current, calculated using formulas in Ref. [8].

However, as seen in Fig. 2, the discharge eventually disrupts. This is mainly attributed to the overly peaked current profile generated by the highly localized central ECCD which is MHD unstable. The time at which the disruption occurs, always $\sim$200 ms after the ECCD is turned on, is of the order of the current redistribution time. Therefore, a broader deposition profile is needed and is obtained by distributing the three EC beams across the minor radius: the first (A) aiming at $\rho_\Phi \approx 0$, the second (B) at $\rho_\Phi \approx 0.3$, and the third (C) at $\rho_\Phi \approx 0.55$ (ρ_Φ is the square root of the normalized toroidal flux). Using this setup we have driven 123 kA of current in a steady-state, fully noninductive scenario for 1.9 s, as shown in Fig. 3, limited only by the 2 s pulse length of our gyrotrons (we use 100 ms to provide a smooth power ramp-up and ramp-down).

The Ohmic transformer current I_{OT} stabilizes very rapidly and is constant for 1.9 s at a value of 14 kA, indicating that no inductive current is driven. The flux induced by the other coils is negligible. The time evolution of I_{OT} is a very sensitive measure of full current replacement, as will be discussed later. The equilibrium profiles relax with a characteristic current redistribution time $\tau_{\mathrm{crt}} \approx 150$ ms, assuming $l_i(t) \sim \exp(-t/\tau_{\mathrm{crt}})$. Therefore we have sustained both the temperature and current profiles with ECCD for more than 900 confinement times and over $10\tau_{\mathrm{crt}}$. The average current-drive efficiency, calculated from the line-averaged density n_{el}, is $\eta_{20\mathrm{CD}} \approx 0.006$ after substraction of about 15% of bootstrap current. These results are consistent with ray-tracing calculations,

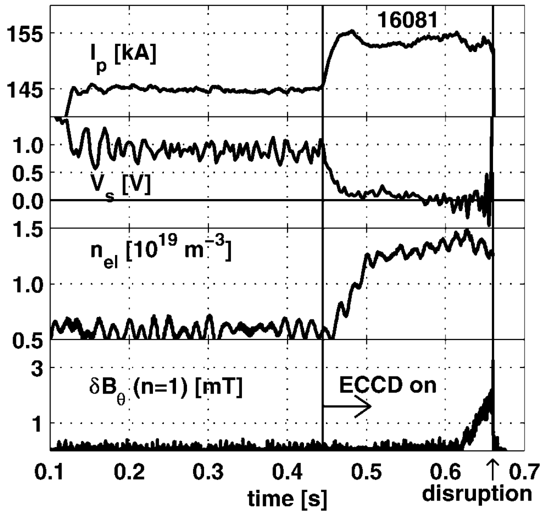

FIG. 2. Transient full current replacement with 1.5 MW deposited near the plasma center and with $I_p = 153$ kA, $n_{e0} \approx 1.75 \times 10^{19}$ m^{-3}. δB_θ is the rms level of poloidal magnetic field fluctuations, indicating MHD activity.

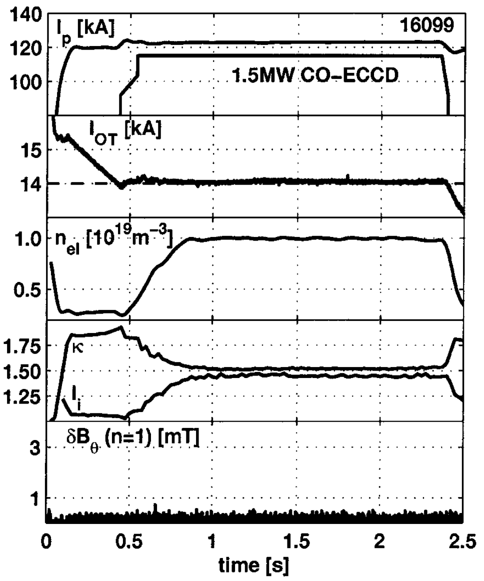

FIG. 3. Steady-state full current replacement with 1.5 MW distributed over the minor radius for 1.9 s with $I_p = 123$ kA, $n_{\mathrm{el}} = 10^{19}$ m^{-3}, $T_{e0} \approx 3.5$ keV. τ_{crt} is estimated to about 150 ms from the time evolution of the plasma inductance l_i and elongation κ, which are inversely proportional as there was no feedback on the elongation. No MHD activity is measured in this scenario, which is limited only by the pulse length of the gyrotrons.

which give 70–120 kA of driven current. Note that there is no MHD activity in this discharge, confirming the good control of the equilibrium profiles. The electron confinement time is about 2.1 ms, better than that expected from the Rebut-Lallia-Watkins scaling law [9] which predicts 1.3 ms for these parameters.

In order to assess the correct match of the preprogrammed plasma current with the total amount of driven and bootstrap current, we show in Fig. 4 a comparison of the discharge of Fig. 3 with two similar discharges with $I_p = 112$ kA and $I_p = 127$ kA. With $I_p = 112$ kA (discharge 16 097) the time derivative of the transformer current is reversed and the Ohmic transformer is recharging. The rate depends on $I_{\mathrm{Ohmic}} = I_p - I_{\mathrm{CD}} - I_{\mathrm{BS}}$ and is in this case 0.25 kA/s. While small, this derivative is clearly visible when compared with the flat case 16 099, and corresponds to a negative surface loop voltage of -0.02 V. In the other case, $I_p = 127$ kA (discharge 16 098), there is not enough noninductive current and a finite slope is seen in I_{OT}, corresponding to $V_s \approx 0.03$ V. The density has not been matched as well and has increased by 10%, leading to a decrease of I_{CD} by about 10%. Therefore these three cases confirm that in these scenarios $I_{\mathrm{CD}} + I_{\mathrm{BS}} = 123$ kA, for $n_{\mathrm{el}} = 10^{19}\ \mathrm{m}^{-3}$, and $I_{\mathrm{Ohmic}} \approx 550 V_s$ (kA). Using a database of nine similar discharges with slightly different I_p, we have obtained an average Ohmic conductance of 640 kA/V.

In these discharges, both the temperature and current profiles are sustained by the beams. However, a question remains concerning the role of the outermost beam, C, at $\rho_\Phi \approx 0.55$: while it does contribute to heating the plasma, the amount of current it is expected to drive is only 2.5–5.5 kA, according to ray-tracing calculations. However, the DIII-D tokamak has shown much larger efficiencies of off-axis ECCD than predicted [10]. According to their results the normalized current-drive efficiency including the local temperature, $\eta_T = 32.6 n_{e20} IR/(T_e P)$, with T_e in keV, is approximately constant across the minor radius with a value around 0.2.

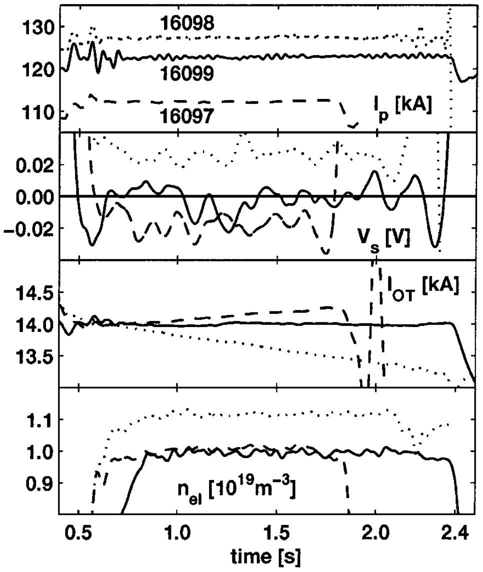

FIG. 4. Comparison of discharge 16 099, solid line, shown in Fig. 3 with discharges 16 097 and 16 098 having I_p set to 112 and 127 kA, respectively. In the first one, the Ohmic transformer is recharging, while in the second it is not. This shows the fine-tuning necessary to obtain a constant Ohmic transformer current.

We have performed two pairs of experiments in order to determine accurately the current driven by gyrotron C. First, we repeated discharge 16 099 with $I_p = 123$ kA but with gyrotron C in the non-current-drive position, that is, $\varphi = 0°$ instead of $\varphi = 35°$: the power deposition was localized at the same radius, adjusting the mirrors slightly according to ray-tracing calculations, in order to obtain the same temperature profile and the same bootstrap current. Only the current driven by this gyrotron should be missing and can be determined from the difference in loop voltage between the two discharges of about 0.013 V [11], corresponding to 7–9 kA of current driven at $\rho_\Phi \approx 0.55$. The local temperature and density are about 1.1 ± 0.2 keV and $1.13 \pm 0.05 \times 10^{19}\ \mathrm{m}^{-3}$, yielding a local efficiency $\eta_T = 0.047 \pm 25\%$. Therefore the outermost beam is contributing to the broadening of the current profile and its efficiency is nearly twice as high as predicted by ray tracing, $\eta_T = 0.024 \pm 50\%$, using the TORAY code [12] with the Cohen package [13]. Although ray-tracing calculations for the small amount of current driven are much less accurate than the experimental results, owing to the uncertainties in the density, temperature, and Z_{eff} profiles, our results confirm the trend seen in DIII-D, even though our local efficiency η_T is at the lower bound of their results at $\rho_\Phi = 0.55$. Note that the current driven off axis is determined very accurately in our case as it is obtained solely with direct experimental measurements using global parameters and in steady-state conditions.

To confirm that we are indeed able to measure an 8% contribution to the plasma current, we compared two discharges with gyrotron C at $\varphi = 0°$ and 35°, respectively, in each case adjusting the plasma current for full current replacement. The results are shown in Fig. 5. Accounting for slight differences in density and in the derivative of the transformer current, we can set the lower bound of the difference in noninductive current between the two discharges at 6 kA. Thus more than 6 kA of current is driven by the gyrotron C, confirming the previous results of 7–9 kA [11] mentioned above. Moreover, we do not have a residual electric field which can modify the wave-particle coupling.

The ray-tracing results indicate that about 68 kA is driven by gyrotron A, and 24 kA by gyrotron B. This gives local efficiencies of $\eta_T \approx 0.15$ near the center and $\eta_T \approx 0.07$ at $\rho_\Phi \approx 0.3$. If one assumes a constant η_T over the minor radius equal to that measured at $\rho_\Phi \approx 0.55$, the beam at $\rho_\Phi \approx 0.3$ would drive about 12 kA and the one at $\rho_\Phi \approx 0$ about 24 kA, for a total of about 44 kA of

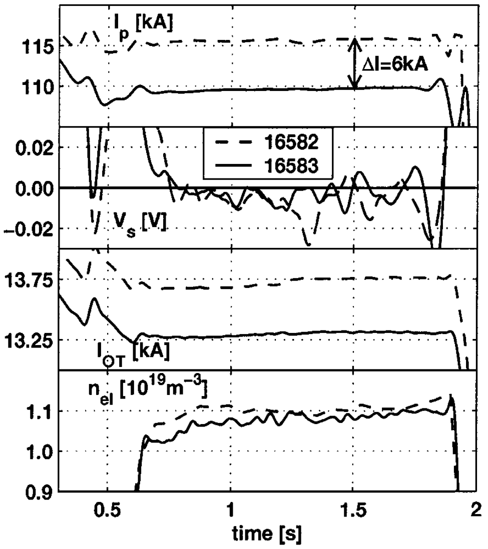

FIG. 5. Full current replacement with three gyrotrons in co-CD position, distributed over the minor radius, dashed line. This is compared with a similar case but with only two gyrotrons in co-CD and the outermost-aiming beam in heating mode, solid line. In the latter case, the Ohmic transformer is recharging less with a line-averaged density slightly lower than in the former case, demonstrating that more than 6 kA of noninductive current is due to the outermost-aiming beam in co-CD.

driven current. This is much smaller than the actual driven current, ≈105 kA, indicating that in our experiments the local current drive efficiency is not constant over the minor radius, contrary to the results of DIII-D [10]. The efficiency decreases as predicted, due to the increased fraction of trapped particles. However, in our case the collisionality ν_{e*} at $\rho_\Phi \approx 0.55$ is smaller, about 0.02, and could explain this discrepancy.

In conclusion, we have demonstrated the steady recharging of the Ohmic transformer at a rate of about 1 kA/s for 1.5 s at $I_p = 80$ kA, $n_{e0} = 1.9 \times 10^{19}$ m^{-3} with 1 MW of on-axis ECCD. We have also shown that we can obtain a steady-state fully noninductive scenario with ECCD only. Using 1.5 MW of power distributed over the minor radius, both the temperature and current profiles are sustained by the beams with $I_p = 123$ kA, $n_{\rm el} = 10^{19}$ m^{-3}, $\eta_{\rm 20CD} \approx 0.006$ for 1.9 s, that is, for about 900 confinement times and over 10 current diffusion times ($\tau_{\rm crt}$). These profiles are MHD stable and the discharges are limited only by the pulse length of our gyrotrons. We obtain a higher current drive efficiency with full ECCD, $\eta_{\rm 20CD} \approx 0.013$ after substraction of the bootstrap current, when all the gyrotrons deposit their energy in the center of the plasma. However, in this case the profiles are overly peaked and the discharge disrupts after typically 100 ms of $V_s \approx 0$ V. We find that the local current drive efficiency is not constant over the minor radius, probably due to the particle trapping effect. Thus, our results are in good agreement with ray-tracing predictions, although the measured efficiency is somewhat higher than calculated at $\rho_\Phi \approx 0.55$.

This work was supported in part by the Swiss National Science Foundation.

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