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Current ramp-up with lower hybrid current drive in EAST

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More economical fusion reactors might be enabled through the cyclic operation of lower hybrid current drive. The first stage of cyclic operation would be to ramp up the plasma current with lower hybrid waves alone in low-density plasma. Such a current ramp-up was carried out successfully on the EAST tokamak. The plasma current was ramped up with a time-averaged rate of 18 kA/s with lower hybrid (LH) power. The average conversion efficiency P_{el}/P_{LH} was about 3%. Over a transient phase, faster ramp-up was obtained. These experiments feature a separate measurement of the L/R time at the time of current ramp up. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4773049]

I. INTRODUCTION

Electrons with thermal velocity $\upsilon_{th} \geq 1/3.5\ \upsilon_{ph}$ can absorb lower hybrid (LH) power, where $\upsilon_{ph} = c/N_{//}$ is the phase velocity of the LH wave. A tail of these superthermal electrons can then carry efficiently the toroidal current in tokamaks.[1] Lower hybrid current drive (LHCD), now the most successful technique for driving non-inductive current, is usually used to achieve steady-state operation of tokamaks,[2] to produce H-mode discharges,[3] to sustain long lasting internal transport barriers during H-mode,[4–7] to suppress tearing modes[8–10] and to modify the current profile.[11] Significant experimental progress in LHCD has been achieved in long-pulse operation of contemporary large tokamaks.[12,13] However, LHCD in high-density plasma suffers from two deficiencies: one, the penetration of high-density plasma is difficult; and two, the efficiency of current drive decreases with the plasma density. Indeed, several LHCD experiments[14–16] have observed a decrease in current drive (CD) efficiency even steeper than the trend $1/n_e$ (expected by quasilinear theory[17]) above a critical density, which indicates that the LH wave will not penetrate the dense plasma center in ITER at the required high density of ITER. The strong wave interactions with plasma density fluctuations at the periphery of plasma column, including the nonlinear mechanism of parametric decay instability, have been suggested as a possible explanation for preventing the penetration of the coupled LH power in the core at high density.[6,7]

Recent experiments in FTU have assessed a new method for enabling LH power penetration at reactor graded high plasma densities by operating with relatively higher electron temperature in the plasma periphery (roughly at $r/a = 1.0$–0.8) and in the scrape-off layer. The presence of LHCD was indicated by the persistence of hard X-ray emission even at $n_{e0} \approx 5 \times 10^{20}\,m^{-3}$ and $n_{e\_0.8} \approx 0.85 \times 10^{20}\,m^{-3}$, beyond what have been considered the upper density limit for LHCD operation.[18] The experimental results were previously predicted by theory of spectral broadening due to parametric instability.[6,7] Following the new route opened by FTU results at high density and aimed at approaching ITER-relevant high-density regimes, more recent LHCD experiments at high densities on C-Mod,[19] JET,[20] Tore Supra,[21] and EAST[22] have been performed.

However, cyclic operation[17] of the LHCD can both overcome the density limitation and reduce the circulating power in tokamak reactors. In this low plasma density regime, the phenomena of physics of the edge, detrimental for LH power penetration in the core, are negligible.[6,7] Moreover, in realizing synergies with alpha channeling,[23] wherein ions can be made hotter than electrons in a reactor, the cyclic operation holds particular promise for economical fusion production.[24] Fig. 1 shows schematically the cyclic operation regime. There are two stages during cyclic operation: the current generation stage, namely the current ramp-up by LH stage, and the current relaxation stage.

The first stage is characterized by plasma with relatively low density and high effective ion charge state Z_{eff}, so that the plasma current can be driven effectively by LH, and simultaneously the current can be ramped up quickly, due to (with larger Z_{eff} or smaller electron temperature) the

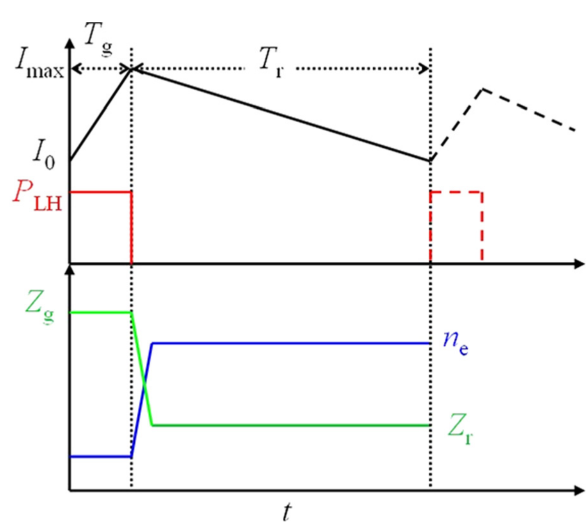

FIG. 1. Schematic of cyclic operation.

relatively short time constant L/R, where L and R are the plasma inductance and the resistivity, respectively. With the current ramped up, the LH power would be converted into poloidal field energy stored in plasma column and then released in the current relaxation stage. During the current relaxation stage, the plasma would be optimized by higher density for greater fusion power and lower effective ion charge state for longer relaxation time. It should be noted that, although higher $Z_{\rm eff}$ in the current ramp-up phase may decrease the steady state CD efficiency according to $J/P_{\rm LH} \sim 1/(5 + Z_{\rm eff})$,[25] the Ohmic countercurrent is even more severely affected. Thus, the average CD efficiency can then be improved by lower $Z_{\rm eff}$ occurring in the second relaxation stage, according to[26]

$$\left\langle \frac{J}{P_{\rm LH}} \right\rangle \equiv \frac{\int_0^{T_g+T_r} J dt}{\int_0^{T_g} P_{\rm LH} dt} \approx \left(\frac{J}{P_{\rm LH}}\right)_{Z=1} \frac{6Z_g}{(5+Z_g)Z_r}, \quad (1)$$

where T_g and T_r are time durations, and Z_g and Z_r are the effective ion charge states for the two stages, respectively. With the plasma current ramped up by LH alone, the central solenoid might be removed in tokamak devices, so that the fusion reactor would be greatly simplified. Moreover, the reactor would operate essentially in the steady state; only the parameters such as density, temperature, or effective ion charge state would cycle.

We report here current ramp-up experiments without using the Ohmic transformer in EAST. These experiments confirm the general tendencies of transformer recharging experiments reported previously.[27–30] In the experiments, the plasma current was ramped up from $I_0 = 194$ kA when 900 kW LH power injected, with which 240 kA current can be fully driven. Namely, the degree of current overdrive here is not high. As a result, the energy conversion efficiency is low, since the current ramp-up rate decreases as the current approaching to the fully driven current. However, in comparison, the experiments offered here feature new experimental techniques that allow us to deduce accurately the degree of overdrive as well as the absorbed spectrum.

II. EXPERIMENTAL SETUP

EAST is a fully superconducting tokamak with a non-circular cross-section vacuum vessel. The poloidal field (PF) magnet system consists of 14 coils, symmetrically located around the equatorial plane as shown in Fig. 2. Coils PF1-PF6 are the central solenoid coils, which mainly provide OH heating power. Coils PF7-PF10 are the divertor coils, controlling of the upper and lower diverter configurations. The external PF coils, PF11–PF14, are the vertical field and shaping coils which mainly control plasma position and shape.[31] The design parameters of EAST are as follows: major radius $R = 1.87$ m, minor radius $a = 0.45$ m, toroidal magnetic field B_t up to 3.5T. The present LHCD system on EAST operates at $f = 2.45$ GHz and consists of 20 main multi-junction waveguides[32] arranged in an array of 5 rows and 4 columns. The $N_{//}$-spectrum radiated from the launcher is usually centered at 2.1 but can be varied between 1.85 and 2.58 by varying the phase difference between adjacent main waveguides from −90° to 180° (note that the phase difference between subwaveguides is fixed).

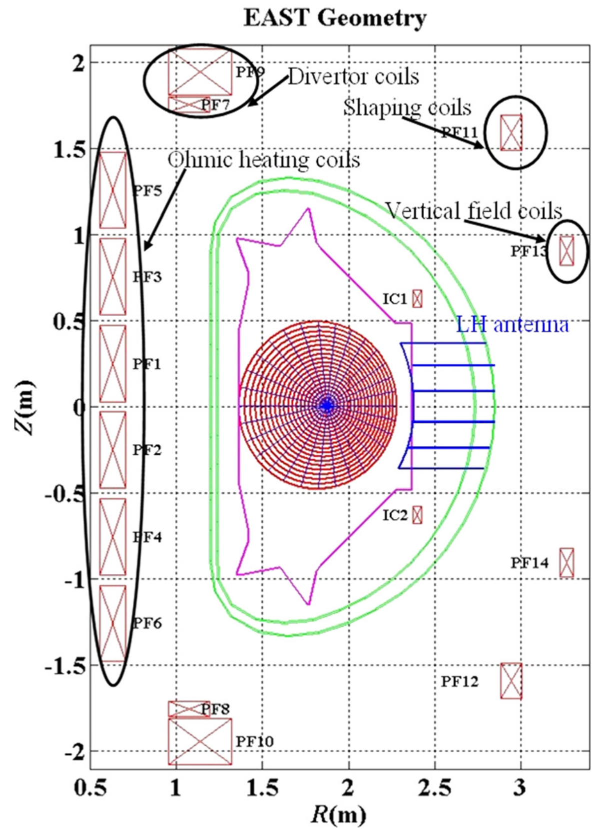

FIG. 2. EAST geometry and locations of PF coils.

III. RESULTS AND ANALYSIS

All the experiments were carried out in the EAST limiter plasma with toroidal magnetic field $B_t = 1.8$ T and a launched LH parallel refraction index $N_{//} = 2.1$. As is well known, the absorbed $N_{//}$ spectrum may differ from the launched $N_{//}$ spectrum, a result that has been predicted theoretically[33,34] as well as deduced experimentally.[35,36] The $N_{//}$ spectrum can be broadened by parametric instability,[6] linear scattering from plasma density fluctuations,[37] and the effects associated with toroidicity.[34] The typical time traces of a current ramp-up discharge with no inductive power input are illustrated in Fig. 3. Note that, during the flattop phase, a plasma with 195 kA steady-state current was maintained by the Ohmic-heating (OH) transformer with a constant loop voltage of 0.7 V, and then, at time $t = 2.99$ s, the current of the OH primary coils was held constant as shown in the bottom box of Fig. 4. With constant primary coil current, there was no inductive voltage contributed from the OH circuit, allowing the plasma current to decay. After a short current decay ($\Delta t \sim 30$ ms), LH power with 900 kW was injected into the deuterium plasma, ramping up the current at an averaged rate of 18 kA/s during the time the density was constant. The discharge was terminated at $t = 4.1$ s, when the LH power was turned off. The ramp-up rate does not remain constant during the full ramp-up stage, but if the LH power is provided for a long enough time, the current should

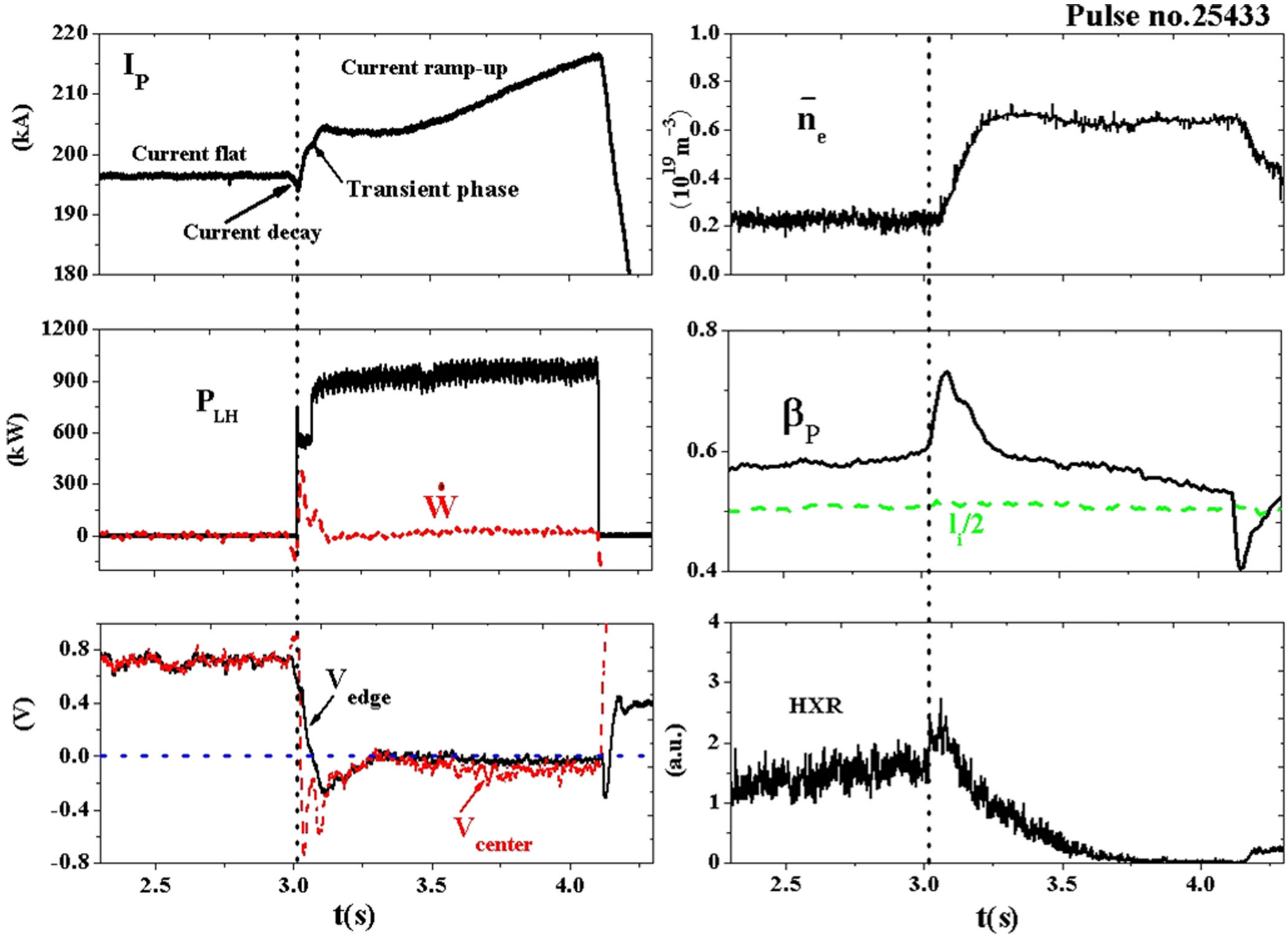

FIG. 3. Typical time traces of current ramp-up by LH.

ultimately approach the steady-state current drive level with $dI/dt = 0$.

The rate of increase of poloidal field energy $W = LI^2/2$ during LH current ramp-up can be expressed as

$$\frac{dW}{dt} = P_{el} - \frac{V^2}{R_{Sp}} + P_{ext}, \quad (2)$$

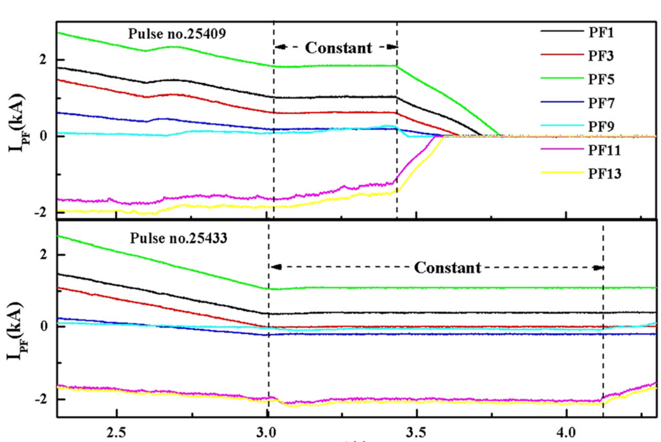

FIG. 4. Time evolution of the PF coil current.

where $P_{el} = -I_{LH} V$ is the LH contribution to the increase in poloidal field energy (note that the loop voltage is negative during ramp-up phase), R_{Sp} is the Spitzer resistance of the plasma, the second term is OH dissipation applied for heating the bulk plasma, and P_{ext} is the external inductive power contributed from the equilibrium field (EF) coils. It should be noted that there is always a finite P_{ext} supplied from the EF coils because the vertical field B_v is also ramped up during current ramp-up to maintain the plasma in equilibrium.

There are two mechanisms for slowing down the hot electrons under current ramp-up conditions: negative electric field and collisions. The energy lost from slowing down by the electric field is converted into poloidal field energy; the energy lost by collisions simply results in heat. We define the efficiency of converting the LH power into the poloidal magnetic field energy as $\varepsilon = (dW/dt)/P_{LH}$. This definition is, for our purposes, essentially the same as the quantity P_{el}/P_{LH}, which is the more usual definition of efficiency.[17] There is little difference in the ramp-up phase; however, because, for slow ramp-up rates, neither the electric field is so large as to cause much Ohmic dissipation nor does the external equilibrium control require much power. For discharge #25433, the rate of increase of W is about 30 kW (after the transient phase). Since the ramp up rate after the transient phase is not so fast, the conversion efficiency is about 3%, as calculated from the above definition.

On the other hand, the earlier transient phase is characterized by a large ramp-up rate and an obviously large increase in poloidal beta β_p as shown in Fig. 3. The poloidal beta, defined as $\beta_p = 8\pi S\langle P\rangle/\mu_0 I_p{}^2$ ($P = n_e T_e$ is the plasma pressure, S is the cross section, and the angle brackets indicate the average over S), is determined by equilibrium fitting (EFIT)[38] equilibrium reconstruction. After the application of the LH wave (typically 2-3 ms), a superthermal electron tail is formed. The energetic tail electrons contribute significantly to the plasma pressure, namely to the β_p increase. Subsequently, the poloidal beta appears to decrease mainly because the energetic electron current reaches saturation, while the full plasma current continues to increase. Since β_p is increased to 0.7, the vertical field B_v must be enhanced in order to maintain the plasma in equilibrium, following the relationship:[39]

$$B_v = \frac{-\mu_0 I_p}{4\pi R}\left[\ln\left(\frac{8R}{a}\right) + \beta_p + \frac{l_i}{2} - \frac{3}{2}\right], \tag{3}$$

where $l_i = \langle B_p(r)^2\rangle/B_p(a)^2$ is the plasma internal inductance. The variation of B_v can be inferred by the evolution of current in coils PF13 and PF14 as shown in Fig. 4, and an external positive voltage is supplied by EF coils. This external voltage allows the loop voltage V_{edge} on $R = 1.37$ m to stay positive even while $dI_p/dt > 0$. As a result, a higher ramp-up rate is obtained during the transient phase. The loop voltage in the plasma center should be negative, at about -0.15 V, as calculated by $V_{center} = V_{edge} - 2\pi R\int_0^a \dot{B}_p dr$.

The hard X-ray signal detected approximately parallel to the LH direction shows that the number of energetic electrons decreases with time, which indicates that the electric field in the plasma is indeed negative. The back current driven by this negative voltage in the bulk plasma is estimated to be 41 kA by Ohm's law $I_b = V_{center}/R_{Sp}$, where the Spitzer resistivity of the plasma is estimated to be 3.6 $\mu\Omega$, using $T_e = 0.9$ keV and $Z_{eff} = 6$, as measured by soft X-ray filter method and visible bremsstrahlung diagnostic, respectively. The important quantity of L/R_{Sp} in the ramp-up stage would then be $\tau_g \sim 1.6$ s with the total self-inductance of plasma loop $L \sim 6\times10^{-6}$ H calculated from $L = \mu_0 R\,[\ln(8R/a) + l_i/2 - 2]$. In addition, the plasma internal inductance remains almost constant throughout, suggesting that the current profile is not changed.

To determine experimentally the time constant L/R_{Sp} in the current ramp-up stage in shot 25433, we consider the reproducibly identical shot, 25409, where instead of applying the rf power at 3.1 s, we instead allow the OH discharge current to decay freely, or to "coast," as shown in Fig. 5. Thus, from shot 25409, we infer the L/R time immediately prior to the current ramp-up stage in shot 25433.

With the rf power turned off and the current in the PF coils held constant from $t = 3.1$ s to $t = 3.4$ s (see Fig. 4), the plasma current decayed gradually with a rate of $k = -144$ kA/s and with a loop voltage of about 0.25 V. This allows us to estimate the time constant L/R_{Sp} to be $\tau_r \sim 0.8$ s, using the definition $\tau = I_0\,(1 - 1/e)/k$. It should be noted that the loop voltage for this case was produced by the variation of the plasma current through the relationship $V_{loop} = -L dI_p/dt$. The differences between two kinds of current decay time (τ_g and τ_r) may be related to the plasma density. The Spitzer resistance is, in principle, independent of density; however, it is indirectly dependent on density since Z_{eff} decreases with density under similar wall conditions, as observed in experiments.

In order to analyze the current ramp-up experiments in detail, a simple model is proposed as follows. Following Ref. 40, the power conversion efficiency P_{el}/P_{LH} can be expressed as

$$\frac{P_{el}}{P_{LH}} = \frac{V_{loop}(I_p - V_{loop}/R_{Sp})}{P_{LH}} \approx \xi u^2, \tag{4}$$

where ξ is a function of Z_{eff}, $u = \upsilon_{ph}/\upsilon_r$, υ_r is the electron runaway velocity defined by $\upsilon_r = |nq^3\ln\Lambda/4\pi\varepsilon_0{}^2 Em|^{1/2}$ and $E = V_{loop}\,/\,2\pi R$. In the case of current ramp-up with LH alone, the loop voltage is given by

$$V_{loop} = -L\frac{dI_p}{dt}. \tag{5}$$

Combining Eqs. (4) and (5), we can obtain

$$\frac{dI_p}{dt} = \frac{1}{L/R_{Sp}}\,(I_{LH} - I_p), \tag{6}$$

where $I_{LH} = \frac{P_{LH}}{n_e R}\frac{2\varepsilon_0^2 m_e \upsilon_{ph}^2 \xi}{e^3 \log\Lambda n_e} = \frac{P_{LH}}{n_e R}\eta_{CD}$ is the current fully driven by P_{LH}, namely the final value of plasma current during ramp-up process. Then, the integral expression of this differential equation can be given as

$$I_p(t) = (I_0 - I_{LH})e^{-\frac{t}{L/R_{Sp}}} + I_{LH}, \tag{7}$$

where I_0 is the initial value of plasma current, and the assumption that CD efficiency η_{CD} remains constant is used. This formula indicates that the plasma current ramps up exponentially with a time constant of L/R_{Sp} and finally reaches a constant value of I_{LH}, which is determined by the LH power P_{LH} and CD efficiency η_{CD}. The modeling results using different values of L/R_{Sp} by using formula (7) are shown in Fig. 6 and the parameters used for the calculation are as follows: $I_0 = 194$ kA, $I_{LH} = 240$ kA (determined by a discharge of full-wave current drive with $P_{LH} = 900$ kW).

The experimental values are thus best modeled by taking $L/R_{Sp} = 1.5$ s (nearly the same as the value of L/R_{Sp} estimated by the Spitzer resistance in LHCD phase), about twice the value with rf heating off during the relaxation. Though the difference between τ_g and τ_r may be related to the plasma density, estimation shows that such difference is mainly explainable by the non-Maxwellian velocity distribution expected after rf heating, due to the so-called *hot conductivity*, as described in Sec. IV. Since P_{el}/P_{LH} has been obtained by the analysis of power flow and ξ is a function of Z_{eff} only, the absorbed value of $N_{//}$ can be calculated by Eq. (4) as 4.2. The absorbed $N_{//}$ is difficult to measure experimentally, and it is generally deduced to be upshifted from the launched $N_{//}$ but not from first principles.

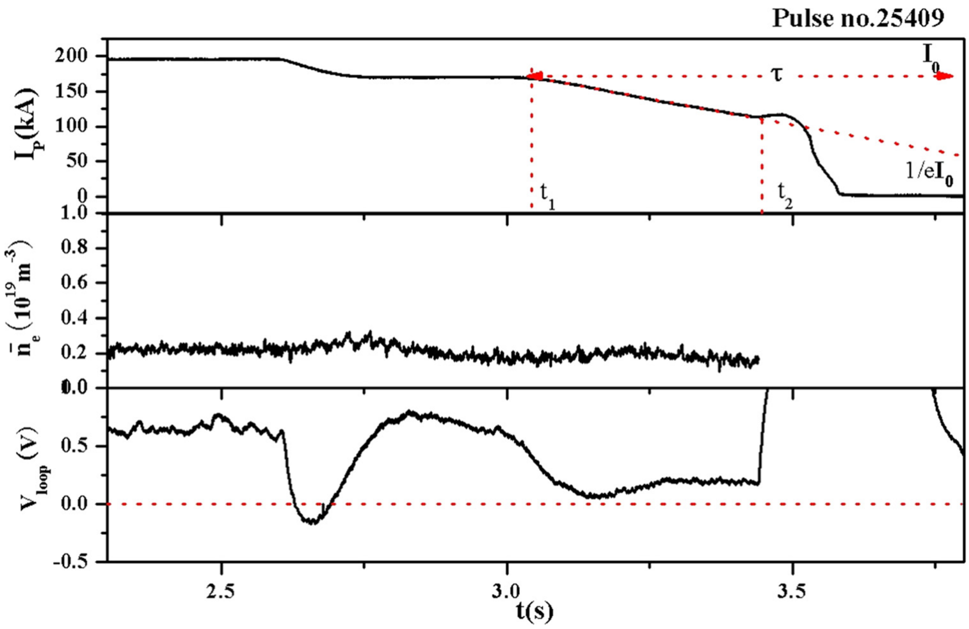

FIG. 5. A typical discharge with plasma current decaying freely.

IV. HOT CONDUCTIVITY

The L/R time is evidently doubled by application of the rf during the ramp up stage. However, the advantage of measuring the L/R time directly prior to this phase is that the degree to which the L/R time changes due to the rf heating can now be seen to be essentially entirely due to the hot conductivity. Note that using Eq. (14) of Ref. 41, we can approximate $J_N \approx 1/8$, since here we have $I_1 = I_{rf}/1$ MA $= 0.24$; $n_1 \approx 0.6$; T1 ≈ 0.9; and, assuming a current channel effectively about half the minor radius, we have $a_1 \approx 0.22$. Since we already deduced that $w \approx 5$ and that $\alpha \approx 0.3$ for $Z = 6$, we can use Eq. (13) of Ref. 32 to deduce that $\sigma_1 \approx \sigma_{Sp}$. Accordingly, the total current during rf can be written as $J_{tot} = \sigma_{Sp}$ E + J_{rf} + σ_1 E +….(where σ_{Sp} E is Ohmic current, J_{rf} is the rf driven current, σ_1 E is the additional current related to hot conductivity σ_1). We can combine the terms linear in E to write $J_{tot} = \sigma_{tot}$ E + J_{rf} +… ~ $2\sigma_{Sp}$ E + J_{rf} +…, where $\sigma_{tot} = \sigma_{Sp} + \sigma_1 \approx 2\sigma_{Sp}$. It means that the L/R time is exactly doubled due to hot conductivity related to rf since the total conductivity during rf application is about twice the value with rf off, in agreement exactly with what was deduced above through modeling the ramp up stage. What we can therefore conclude is that the non-Maxwellian features giving rise to the increased conductivity are in fact due essentially to the hot conductivity, rather than due to a change in the Spitzer conductivity itself through effective Z or electron temperature. The distinction is that the hot conductivity is directly proportional to the rf absorbed power, in a manner that can be inferred from first principles.

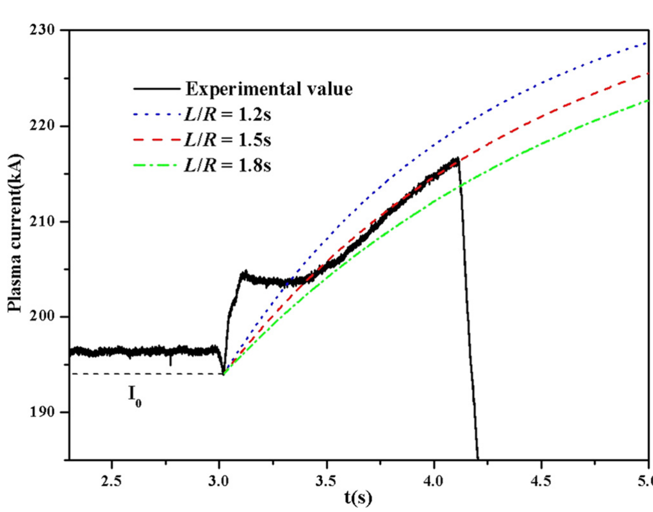

FIG. 6. Modeling results of LH current ramp-up with different values of L/R_{Sp}.

V. SUMMARY

Plasma current ramp-up without using the Ohmic heating solenoid and transformer recharging have been demonstrated for the first time on the EAST fully superconducting tokamak. The time evolution of a typical current ramp-up discharge is reported. The experimental results are interpreted using a circuit equation model. The ramp-up rates and efficiencies reported are not large, because the L/R times are relatively large due to the large size of EAST. To increase the efficiencies, the ramp-up should be as high as possible and in overdrive, namely the condition, $I_{LH} \gg I_p$, should be satisfied. The direct way would be simply to increase I_{LH}. A second way may be to inject impurities to lower the L/R time. The impurities increase the resistivity directly, and if they radiate, might indirectly increase the resistivity by lowering the temperature.

The key innovations here are the experimental techniques for measuring L/R times empirically, by arranging for a decay of the plasma current over a very short time. This can be done by having a short decay prior to the LH injection (prior to transient stage) or immediately upon the termination of the LH wave power (coasting stage). The L/R times thus directly determined are consistent with the L/R time inferred through separate determination of the plasma parameters, but the direct measurement is clearly more reliable. Using the empirically determined L/R time, the $N_{//}$ absorbed spectrum can then be estimated to be 4.2, at least in the ramp-up stage, through the circuit equations that give the efficiency. Using the inferred $N_{//}$ absorbed spectrum, we can determine that the hot conductivity is comparable to the Spitzer conductivity, meaning that the rf absorption itself accounts for the full distortion of the electron distribution function during the ramp up stage, rather than any change in effective Z or electron temperature. This description relies on the novel, empirical measurement of the L/R time immediately prior to the ramp up stage.

This work is preliminary; after EAST undergoes its scheduled upgrade, which will equip it with much higher rf power (the maximal output power is designed to be 4 WM with $f = 2.45$ GHz), we plan to investigate further the cyclic operation regime in EAST, including attaining higher ramp-up rates, making use of the experimental techniques outlined here. In particular, in view of the results here, there is the expectation that the ramp up rate will be impeded most by the hot conductivity. Therefore, ways of interfering with this conductive channel will be important to reach the highest ramp up rates.

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