Startup and Quasistationary Drive of Plasma Current by Lower Hybrid Waves in a Tokamak

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A plasma current is initiated and raised to a quasistationary level of about 20 kA by injection of the lower hybrid wave into a cold and low-density plasma produced by electron cyclotron resonance. The plasma current rises more slowly than the experimentally obtained L_p/R_p magnetic diffusion time of the bulk plasma. The current rise time is inversely proportional to the bulk electron density, and agrees well with the collision time of the current-carrying high-energy electrons with the bulk plasma.

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A plasma current generated by an Ohmic heating electric field is maintained by injecting lower hybrid waves (LHW) in many tokamaks.[1-6] These experimental results demonstrate the possibility of a steady-state operation in a future large tokamak. The startup of plasma current by a noninductive method is attractive for the further saving of the volt-seconds of the Ohmic heating transformer. Recently, experiments on current-startup by LHW have been tried in a target plasma produced by LHW alone[7] or by electron cyclotron resonance (ECR).[8] In the WT-2 tokamak, the plasma current increases linearly in time. However, the quasisteady state is not attained since the pulse duration of LHW is relatively short. The realization of the quasisteady state in the plasma current initiated by rf is necessary to clarify the mechanisms of the startup and quasistationary drive and to establish the startup scenario in a future large tokamak.

In this Letter, we report on the startup and quasistationary drive of the plasma current by LHW in which the pulse width (= 170 ms) is much longer than the experimentally obtained L_p/R_p time, where L_p and R_p are the total inductance and resistance of the bulk plasma. The experiments are carried out on the Japanese Institute of Plasma Physics T-IIU tokamak (major radius $R_0 = 0.93$ m and minor radius $a_L = 0.25$ m). First, a cold and low-density target plasma is produced by the electron cyclotron wave of an ordinary mode ($f = 35.5$ GHz) which is injected from the low-field side.[9] The electron cyclotron-resonance layer (ECR layer) is located at $R = 0.91$ m where the toroidal field B_t is 1.27 T. The initial filling-gas pressure P is 5×10^{-5} Torr for hydrogen. The electron temperature and density of the ECR plasma are about 20 eV and 2×10^{12} cm^{-3}, which are measured by a movable floating double probe. Next, the LHW is injected into the ECR plasma via the launcher of a pair of C-shaped waveguides.[4] The calculated spectrum of the power emitted from the waveguides has a wide spread of parallel refractive index ($n_\parallel$) from 4 to 1.4, which corresponds to a critical value of the accessibility condition for $\bar{n}_e = 2\times10^{12}$ cm^{-3}. In the current startup by rf alone, it is particularly essential to control the vertical field carefully. A quasistationary vertical field of about 10 G is always applied at the beginning of the LHW pulse to bring the Larmor radius of a high-energy electron beam inside the vacuum vessel,[10] where the stray field is estimated at below 2 G under this experimental condition. The feedback-controlled vertical field is also applied together with the LHW pulse. It should be noted that the inductive loop voltage due to vertical fields is less than 0.1 V. The electron density is widely changed from (0.8 to 4)$\times10^{12}$ cm^{-3} by gas puffing to investigate the effect of the bulk electron density on the current startup and drive. The primary coils of the Ohmic heating transformer are short circuited to prevent the iron core from magnetization.

Figure 1 shows typical wave forms for the lower [$\bar{n}_e = (1\text{–}2)\times10^{12}$ cm^{-3}] and higher [$\bar{n}_e = (2.5\text{–}3.5)\times10^{12}$ cm^{-3}] density plasmas. Top traces in Fig. 1 show the powers of electron cyclotron heating (ECH) and LHW. The LHW pulse is applied 7 ms after the initiation of the ECH pulse (width 15 ms, power 20 kW). The plasma current rises with a characteristic rise time τ_r and approaches the steady-state value I_{pm}. The rise time τ_r clearly depends on the bulk electron density $\bar{n}_e$, i.e., $\tau_r \cong 60$ ms for the lower-density discharge and about 30 ms for the higher one, although I_{pm} does not clearly depend on $\bar{n}_e$ contrary to the theoretical prediction. The rise time is considerably longer than the measured L_p/R_p time of about 5 ms for

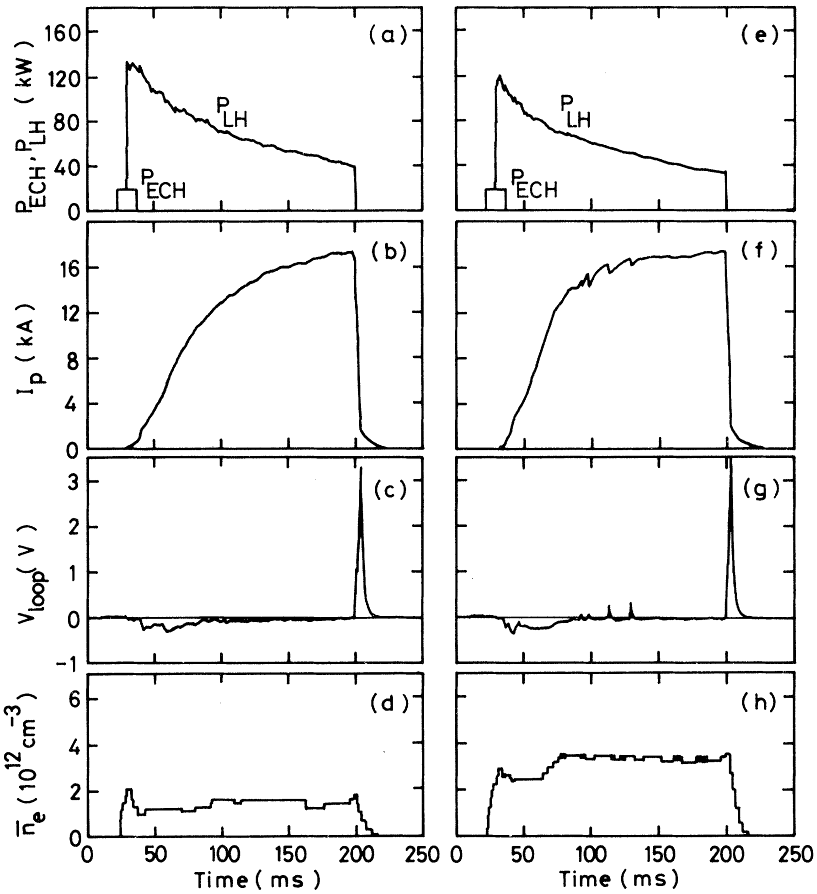

FIG. 1. Typical wave forms of the lower- and higher-density discharges. (a),(e) ECH and LHW power; (b),(f) plasma current; (c),(g) loop voltage; (d),(h) line-averaged bulk electron density. $B_t = 1.27$ T and $P = 5\times10^{-5}$ Torr H_2.

$Z_{\mathrm{eff}} \cong 4$, where the Z_{eff} value is estimated from vacuum ultraviolet spectroscopy.

Figure 2 shows several traces related to the high-energy electrons in a typical plasma initiated by rf power under almost the same condition as Fig. 1. The distinctive feature of this tokamak plasma is a markedly large value of $\beta_p + l_i/2$, and usually $\beta_p \times (a_L/R_0) \gtrsim 0.5$ on the assumption of $l_i = 1$. This enhancement of β_p is due to a large amount of high-energy electrons, since the contribution of the bulk plasma is rather small ($\beta_p^{\mathrm{bulk}} \lesssim 0.2$). From the signal of β_p, the high-energy electron density is estimated as about 1% of $\bar{n}_e$ during the quasistationary phase for the effective tail electron temperature $T_{\mathrm{et}} = 30$ keV, where the measured x-ray spectra ($10 \lesssim E \lesssim 150$ keV) exhibit an exponentially falling tail with $T_{\mathrm{et}} = 20$–50 keV. The intensity of the X-mode second-harmonic electron cyclotron emission (ECE) from the plasma center increases with the increase of plasma current. During the discharge the trace exhibits some abrupt increases which result from the Parail-Pogutse tail anisotropy instability.[11] The time behavior of ECE implies that the perpendicular electron temperature of the plasma is substantially enhanced on the time scale of the current rise time, since the ECE mainly reflects the perpendicular motion of electrons.

It should be noted that as seen from Figs. 1 and 2 the plasma current just after the LHW pulse decays more rapidly than the current rise time. The decay time is roughly comparable to the L_p/R_p time of the bulk plasma. The phenomena are explained as follows: The rf current is instantaneously shut off by the above-mentioned tail anisotropy instability triggered by the positive loop voltage which corresponds to a fraction of the Dreicer field. The evidence for the instability is shown by the sharp spike on the ECE signal at the end of the LHW pulse.

We summarize the observed current rise time τ_r as a function of $\bar{n}_e$ by the open circles in Fig. 3. This figure shows that τ_r is inversely proportional to $\bar{n}_e$. It should be noted that as seen from Figs. 1

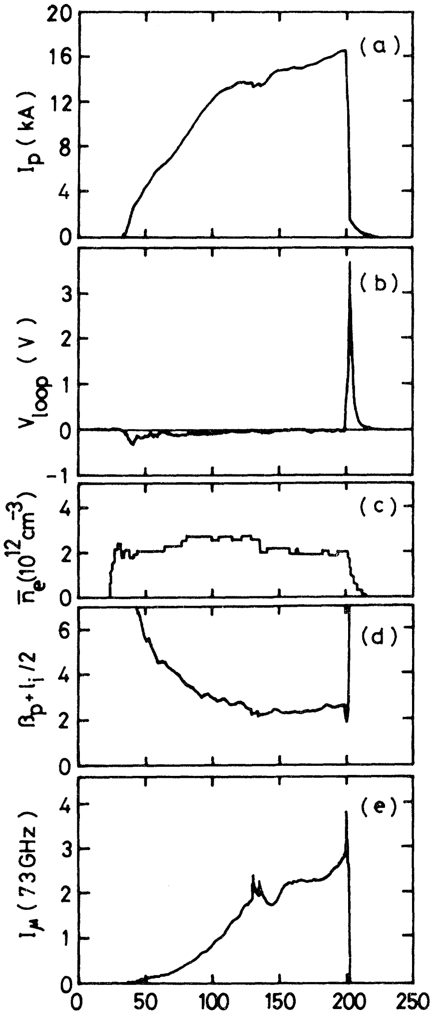

FIG. 2. Time behavior of typical quantities related to high-energy electrons: (a) plasma current, (b) loop voltage, (c) bulk electron density, (d) $\beta_p + l_i/2$ which is derived from a pair of magnetic probes, and (e) electron cyclotron emission.

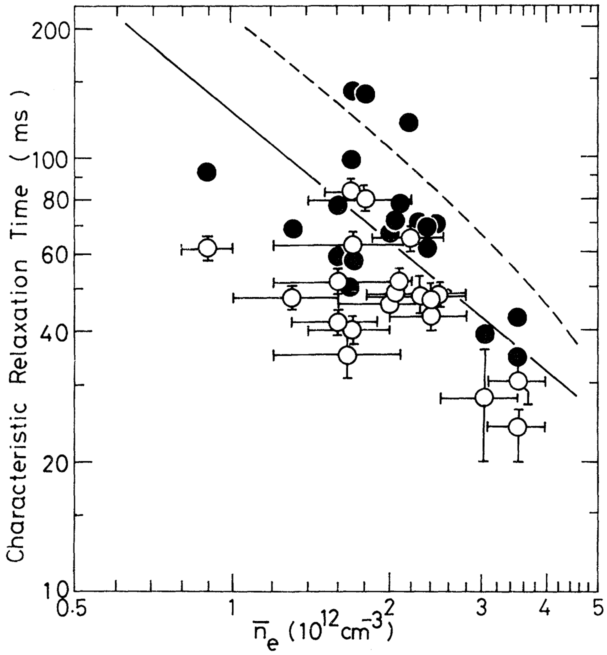

FIG. 3. Dependence of several characteristic relaxation times on bulk electron density. Open circles: observed current rise time. Solid circles: current rise time corrected by the time decay in the LHW power. Solid line: collision time of the current-carrying high-energy electrons of $T_{\rm et} = 35$ keV with the bulk plasma. Broken curve: rf current turn-on time estimated by the quasilinear theory.

and 2 the LHW power decreases appreciably in time with a characteristic decay time of about 150 ms. The decay is due to the use of capacitor banks as a power supply for anode-modulated klystrons. The decay in the power has a tendency to reduce the current rise time. The solid circles in Fig. 3 show the rise time estimated from τ_r by the correction for the time decay in the LHW power (τ_r^*), i.e., this current rise time corresponds to that on a steplike wave form of the LHW power. These are also inversely proportional to $\bar{n}_e$. The τ_r^* corrected for current rise time agrees well with the collision time of the high-energy electrons $T_{\rm et} = 35$ keV with the bulk electrons and ions (solid line in Fig. 3). According to the quasilinear theory,[12,13] the current rise time is called the rf current turn-on time $\tau_{\rm to}$, and is expressed as $\tau_{\rm to} \cong 6[w_2 - w_1]^{1/2} w_1^2 \tau_{ee}$, where τ_{ee} is e-e collision time of a bulk electron, and w_1 and w_2 are the lower and upper parallel velocities of the resonant region normalized by electron thermal velocity. The broken curve in Fig. 3 shows the turn-on time estimated from $n_{\parallel \min} \leq n_\parallel \leq 4$ and the spatially averaged electron temperature $\langle T_e \rangle = 30$ eV. The value of $n_{\parallel \min}$ is determined by the accessibility condition of LHW. The theoretically obtained curve is quite close to the experimental data. It is concluded that the equilibrium state in a parallel electron distribution function deformed by LHW is dominated by Coulomb collision processes, i.e., slowing down and pitch-angle scattering of the current-carrying high-energy electrons due to the bulk plasma.

We discuss the effects of direct loss of the high-energy electrons and return current on the current rise by LHW. The direct loss of the electrons is almost neglected when $I_p \gg I_A/(2A)$, where I_A is the Alfvén current and A an aspect ratio of the plasma.[14] The electrons with a typical energy of 30 keV are well confined with $I_p >> 0.5$ kA, since $I_A \cong 4$ kA and $A \cong 4$. We observe the bulk electron heating (20 eV to about 100 eV) due to a return current during the initial phase when the appreciable negative loop voltage appears. However, the effect of return current can be also neglected, since it is as low as about 3 kA.

The current drive efficiency is estimated as $F = I_{pm}\bar{n}_e R/P_{\rm LH} \approx 10^{14}$ A/W/cm^2 for $\bar{n}_e \cong 2\times10^{12}$ cm^{-3}, where $P_{\rm LH}$ is the LHW power at the end of the pulse ($15 \lesssim P_{\rm LH} \lesssim 50$ kW) and $R \cong 90$ cm. The efficiency is close to the empirical scaling with T_e dependence.[15] However, it is smaller by one order of magnitude than that from the quasilinear theory. Typically 5% of rf input is converted into a poloidal magnetic energy. Around 10% of $P_{\rm LH}$ is consumed to store the magnetic energy dominantly during the current-rise phase, and then the same amount to compensate a collisional loss to the bulk plasma in the quasisteady state. The rest of $P_{\rm LH}$ is lost through unmonitored channels such as rf leakage, plasma production, and radiation. It should be noted that $\tau_{\rm rise}$ is dominated by a collisional loss time of high-energy electrons, while I_{pm} depends on the product of the loss time and the production rate. This can explain that $\tau_{\rm rise}$ follows the theoretical prediction in spite of the discrepancy in F. Moreover, the weak dependence of $I_{pm}/P_{\rm LH}$ on $\bar{n}_e$ in Fig. 1 suggests that the production rate of high-energy electrons is approximately proportional to $\bar{n}_e$ as well as $P_{\rm LH}$. In T-IIU, the current startup has been successfully carried out, being independent of ECH power ($\lesssim 30$ kW). The number of high-energy electrons that directly interact with LHW appears to be negligibly small in the cold ECR plasma. Unidentified mechanisms such as parametric instabilities and toroidal upshift of $n_\parallel$ may play an essential role for connecting the high-energy resonant region with the low-energy region of the bulk plasma.

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