INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

Start-Up and Quasi-Stationary Drive of Plasma Current by Lower Hybrid Wave in the JIPP T-IIU Tokamak

K. Toi, K. Ohkubo, K. Kawahata, Y. Kawasumi, K. Matsuoka,
N. Noda, Y. Ogawa, K. Sato, S. Tanahashi, T. Tetsuka,
E. Kako, S. Hirokura, Y. Taniguchi, S. Kitagawa,
Y. Hamada, J. Fujita and K. Matsuura

(Received - Jan. 31, 1984)

IPPJ- 667 Feb. 1984

RESEARCH REPORT

NAGOYA, JAPAN

Start-Up and Quasi-Stationary Drive of Plasma Current by Lower Hybrid Wave in the JIPP T-IIU Tokamak

K. Toi, K. Ohkubo, K. Kawahata, Y. Kawasumi, K. Matsuoka,
N. Noda, Y. Ogawa, K. Sato, S. Tanahashi, T. Tetsuka,
E. Kako, S. Hirokura, Y. Taniguchi, S. Kitagawa,
Y. Hamada, J. Fujita and K. Matsuura

(Received - Jan. 31, 1984)

IPPJ- 667 Feb. 1984

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan.

Abstract

A plasma current is initiated and raised up to a quasi-stationary level of about 20 kA by injecting 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 decreases with the increase of the bulk electron density, and agrees well with the collision time of the current-carrying high energy electrons with the bulk plasma.

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 a possibility of a steady-state operation in a future large tokamak. The start-up of plasma current by non-inductive method is attractive for the further saving of the volt-seconds of the ohmic heating transformer. Recently, the current start-up experiments by LHW are 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 quasi-steady state is not attained since the pulse duration of LHW is relatively short. The realization of the quasi-steady state in the plasma current initiated by rf is necessary to clarify the mechanisms of the start-up and quasi-stationary drive and to establish the start-up scenario in a future large tokamak.

In this letter, we report on the start-up and quasi-stationary 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 JIPP 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 x 10^{-5} torr for hydrogen. The electron temperature and density of the ECR-plasma are about 20 eV and 2 x 10^{12} cm^{-3}, which are measured by a movable floating double probe. Next, 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 spreading of a parallel refractive index ($n_{\parallel}$) from 4 to 1.4, which corresponds to a critical valve of the accessibility condition for $\bar{n}_e = 2 \times 10^{12}$ cm^{-3}. In the current start-up by rf alone, it is particularly essential to control the vertical field carefully. A quasi-stationary 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 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 x 10^{12} cm^{-3} by gas puffing to investigate the effect of the bulk electron density on the current start-up and drive. The primary coils of the ohmic heating transformer are short-circuited to prevent the iron core from magnetization.

Figure 1 shows typical waveforms for the lower ($\bar{n}_e$ = 1-2 x 10^{12} cm^{-3}) and higher ($\bar{n}_e$ = 2.5-3.5 x 10^{12} cm^{-3}) density plasmas. Top traces in Fig.1 show the powers of 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 (Figs.1(b) and (f)) rises up with a characteristic rise time τ_r and approaches to the steady-state value I_{pm}. As seen from these traces, τ_r clearly depends on the bulk electron density $\bar{n}_e$, that is, $\tau_r \cong 60$ ms for the lower density discharge and about 30 ms for the higher one. The rise time is considerably longer than the measured L_p/R_p-time of about 5 ms for $Z_{eff} \cong 4$, where Z_{eff} value is estimated from VUV 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 considerably large value of $\beta_p + l_i/2$, and usually $\beta_p(a_L/R_0) \gtrsim 0.5$ 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 considerably small ($\beta_p^{bulk} \leq 0.2$). From the signal of β_p, the high energy electron density is estimated as about 1 % of $\bar{n}_e$ during the quasi-stationary phase for the effective tail electron temperature T_{et} = 30 keV, where the measured X-ray spectra ($10 \leq E \leq 150$ keV) exhibit an exponentially falling tail with T_{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 a 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 considerably 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 comprable 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 of 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 decreases with the increase of $\bar{n}_e$. It should be noted that as seen from Figs.1 and 2 the LHW power appreciably decreases in time with a characteristic decay time of about 150 ms. The decaying is due to use of capacitor banks as a power supply of anode-modulated klystrons. The decaying in the power has a tendency to reduce the current rise time. The solid circles in Fig.3 shows the rise time estimated from τ_r by the correction for the time-decaying in the LHW power (τ_r^*), i.e., this current rise time corresponds to that on a step-like waveform of the LHW power. These also decrease with the increase of $\bar{n}_e$. The current rise time corrected τ_r^* agrees well with the collision time of the high energy electrons of T_{et} = 35 keV with the bulk electrons and ions (solid line in Fig.3). According to the quasi-linear theory,[12,13] the current rise time is called the rf current turn-on time τ_{t-o}, and is expressed as $\tau_{t-o} \cong 6[w_2 - w_1]^{1/2} w_1^2 \tau_{ee}$, 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 on $n_{\parallel min} \leq n_\parallel \leq 4$ and 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 considerably 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 process, 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 on $I_p \gg I_A/(2A)$, where I_A is the Alfvén current and A an aspect ratio of a plasma.[14] The electrons with a typical energy of 30 keV are well-confined when $I_p \gg 0.5$ kA, since $I_A \cong 4$ kA and A $\cong$ 4. We observe the bulk electron heating due to a return current during the initial phase of the current-rise when the appreciable negative loop voltage appears. In our experiments, the return current is estimated not so large as about 3 kA, therefore the effect does not essentially alter the above conclusions on the current rise time.

Typically, about 5 % of the total LHW input is converted into the poloidal magnetic field energy. The current-drive efficiency has been estimated as $F = I_{pm}\bar{n}_e R/P_{LH} \cong 10^{14}$ A/W/cm^2, where P_{LH} is the LHW power at the end of the pulse. The scanning range of P_{LH} and $\bar{n}_e$ are as follows: $15 \le P_{LH} \le 50$ kW and $0.8 \le \bar{n}_e \le 4 \times 10^{12}$ cm^{-3}. The major plasma radius is nearly fixed at $R \cong 0.9$ m. The efficiency F is smaller by one order of magnitude than that from the quasi-linear theory. The above efficiency, however, has good agreement with the empirical relationship of $I_{pm}\bar{n}_e R/P_{LH} \cong 8 \times 10^{14}\ T_e$ (keV) which has been derived from the experiments in the ohmically heated plasmas,[15] where in this experiment the electron temperature on a magnetic axis is increased from 20 eV to about 100 eV due to a return current and kept around 100 eV by a power flow from the high energy electrons. In JIPP T-IIU, the current start-up has been successfully carried out, being independent of the ECH power ($0 \leqq P_{ECH} \le 30$ kW). The number of the high energy electrons directly interact with LHW appears to be negligibly small in the cold ECR plasma. The unidentified mechanisms such as toroidal upshift of $n_\parallel$ and parametric instabilities may play an essential role for connecting the high energy resonant region with the low energy region of the bulk plasma.

In conclusion, the considerably low density start-up with appropriate phase velocity modulation is advantageous for the rf start-up in a future large tokamak.

The authors would like to thank Drs. M. Mimura and K. Matsumoto for their cooperation in the plasma measurements, and the members of R-project design team for their encouragements of this work.

References

1. T. Yamamoto et al., Phys. Rev. Lett. 45, 716 (1980).
2. M. Nakamura et al., Phys. Rev. Lett. 47, 1902 (1981).
3. S. C. Luckhardt et al., Phys. Rev. Lett. 48, 152 (1982).
4. K. Ohkubo et al., Nucl. Fusion 22, 203 (1982).
5. S. Bernabei et al., Phys. Rev. Lett. 49, 1255 (1982).
6. M. Porkolab et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 9th Int. Conf. Baltimore, 1982) Vol.1, IAEA, Vienna (1983) 227.
7. W. Hooke, Plasma Physics and Controlled Fusion 26, 133 (1984), which is the invited paper presented in 11th European Conference of Europ. Phys. Soc. Plasma Phys. Div.
8. S. Kubo et al., Phys. Rev. Lett. 50, 1994 (1983).
9. K. Ohkubo et al., Nucl. Fusion 22, 1085 (1982).
10. E. Ott and R. N. Sudan, Phys. Fluids 14, 1226 (1971).
11. V. V. Parail and O. P. Pogutse, Sov. J. Plasma Phys. 2, 125 (1976).
12. N. J. Fisch, Phys. Rev. Lett. 41, 873 (1978).
13. C. F. F. Karney and N. J. Fisch, Phys. Fluids 22, 1817 (1979).
14. H. Knoepfel and D. A. Spong, Nucl. Fusion 19, 785 (1979).
15. Y. M. Peng, P. H. Rutherford et al., "FED-A an Advanced Performance FED Based on Low Safety Factor and Current Drive", ORNL/FEDC-83/1.

Figure Captions

Fig.1 Typical waveforms of the lower and higher density discharges. (a) and (e): ECH and LHW power, (b) and (f): plasma current, (c) and (g): loop voltage, and (d) and (h): line-averaged bulk electron density. B_t = 1.27 T and P = 5 x 10^{-5} TorrH_2.

Fig.2 Time behaviors of typical quantities related to high energy electrons; (a): plasma current, (b): loop voltage, (c): bulk electron density, (d): $\beta_p + \ell_i/2$ 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-decaying in the LHW power. Solid line: collision time of the current-carrying high energy electron of T_{et} = 35 keV with the bulk plasma. Broken curve: rf current turn-on time estimated by the quasi-linear theory.

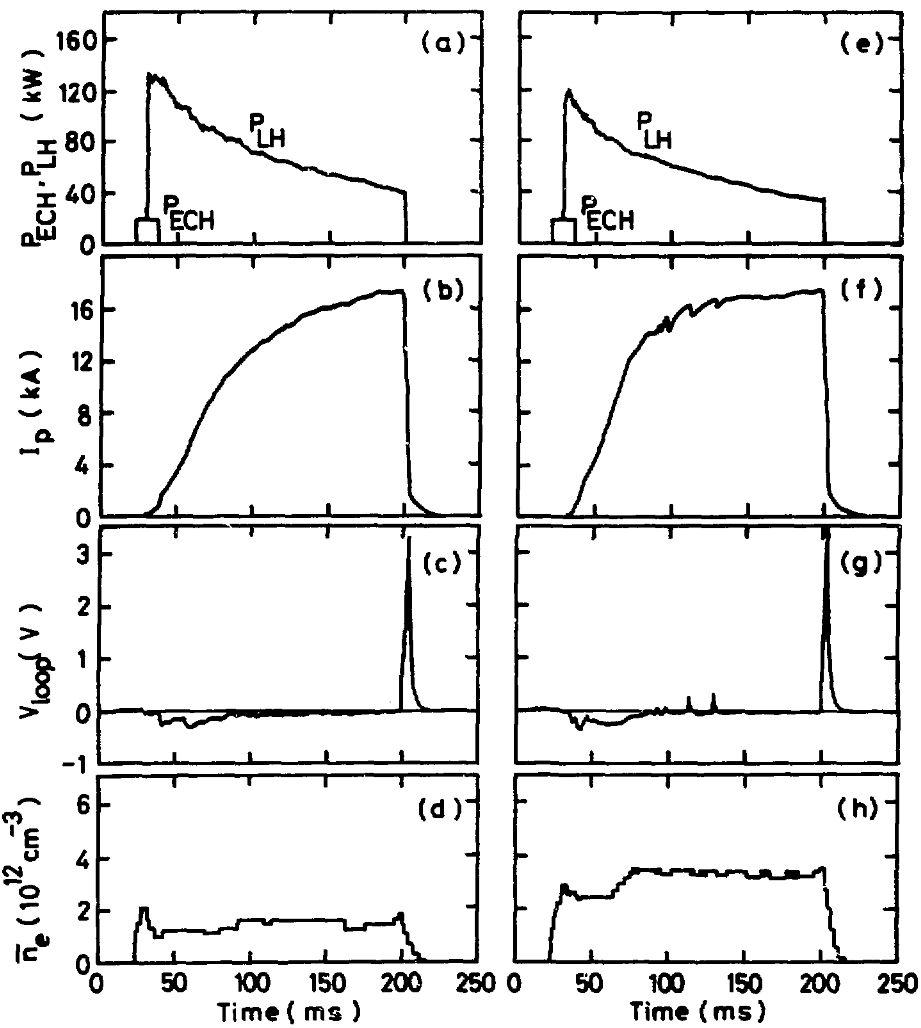
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
P_{ECH}, P_{LH} (kW)
P_{LH}
P_{ECH}
I_p (kA)
V_{loop} (V)
$\bar{n}_e$ (10^{12} cm^{-3})
Time (ms)
Time (ms)

Fig.1

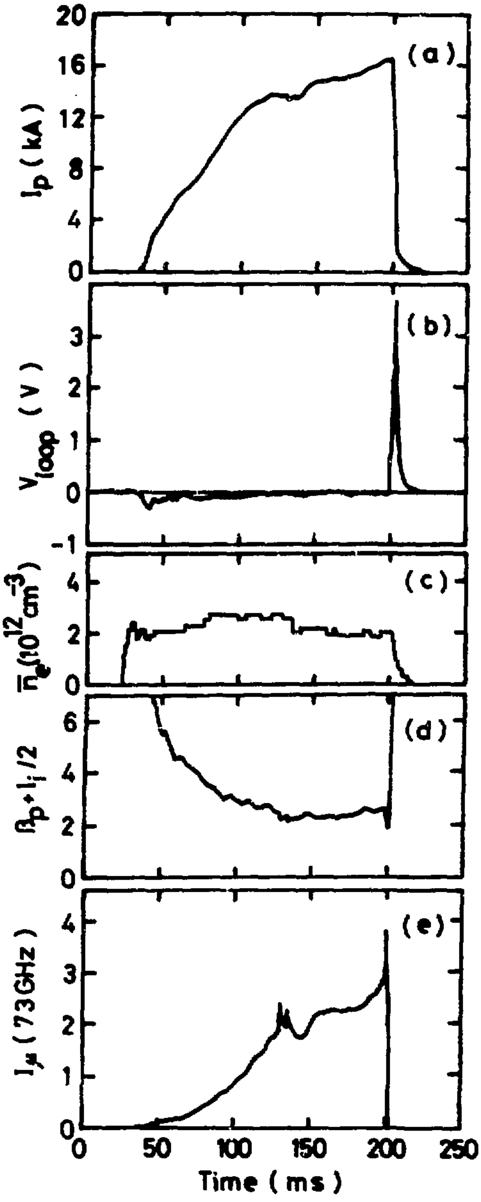

Fig.2

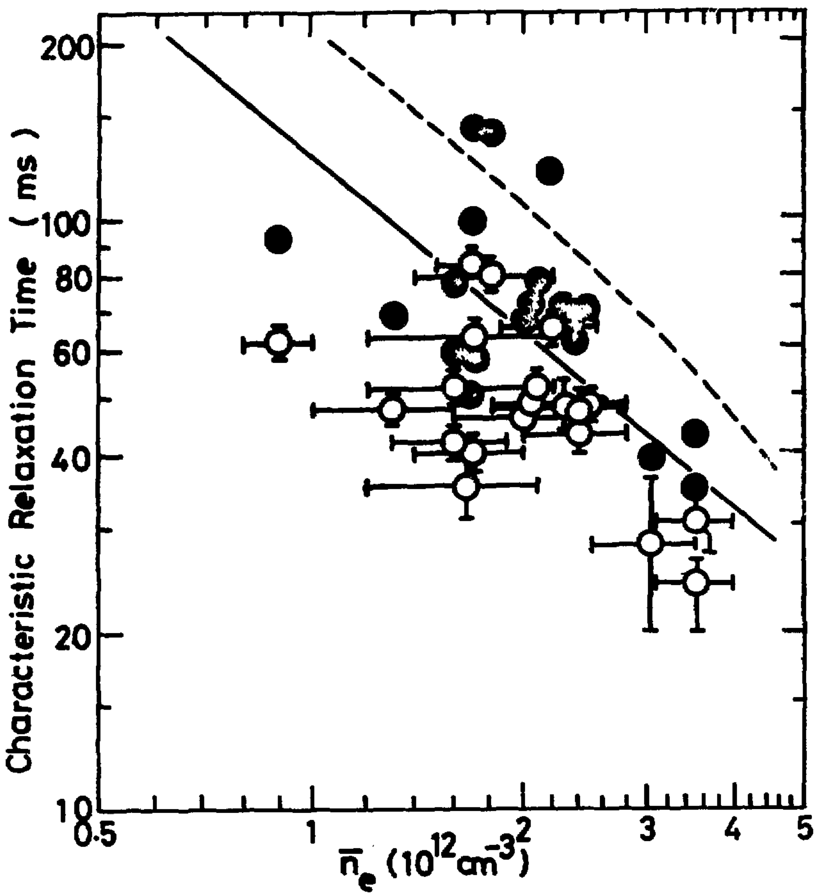
Characteristic Relaxation Time (ms)
200
100
80
60
40
20
10
0.5
1
2
3
4
5
n̄e (10^12 cm^-3)

Fig.3