Current ramp-up experiments in full current drive plasmas on TRIAM-1M

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Abstract. Four types of plasma current ramp-up experiments were executed on TRIAM-1M in full lower hybrid current drive plasmas (LHCD: 8.2GHz, up to 0.4 MW, 8 x 2 grill antenna); 1) the current start up by the combination between electron cyclotron resonance heating (ECH: 170GHz, up to 0.2 MW, O-mode launching) and LHCD at the density of ~2×10^{19}m^{-3} at B_t=6.7T, 2) the tail heating by the additional LHCD, 3) the bulk heating by ECH, 4) the spontaneous ramp up by the transition to enhanced current drive (ECD) mode. The time evolutions of plasma current during four types of ramp-up phase were investigated and an exponential type and a tangent-hyperbolic one were observed. The time evolutions of plasma current during the tail and the bulk heating show the exponential type except the tail heating with high $n_{//}$ and it has a tangent-hyperbolic one during the ECD mode and the current start-up. A simple model with two different time constants, which are a time defined by L/R, $\tau_{L/R}$, and a time caused by change of the effective refractive index along the magnetic field, τ, is proposed to explain two types of the time evolution of the plasma current. The estimated $\tau_{L/R}$ is consistent with the calculated one from the plasma parameter. It is found that τ are less than $\tau_{L/R}$ in the cases of the tail and the bulk heating, and comparable in the cases of the ECD mode, and more than $\tau_{L/R}$ in the cases of the plasma start-up. This indicates that the value of the effective refractive index along the magnetic field, $\langle n_{//}\rangle$, develops during the ECD mode and the current start-up. The value of τ depends on the RF power. The estimated $\langle n_{//}\rangle$ is close to the expected up-shifted $n_{//}$ due to the toroidal effect and the magnetic shear.

1. Introduction

A plasma current control technique in full non-inductive current drive plasmas is an indispensable technique in steady state operation of tokamaks. As the plasma current in high β tokamak will be mainly sustained by bootstrap current, the degradation of plasma confinement leads to the decreasing of the plasma current and then the confinement becomes worse. Hence, the current ramp-up technique without inductive assistance will be required to avoid this positive feedback loop between the confinement and the plasma current. In fully non-inductive current drive plasmas, the plasma current is determined by the non-linear coupling of various plasma parameters, because the current drive efficiency is affected by the electron density, temperature, and so on and the boot strap current is also affected directly by the plasma pressure. It is necessary to develop the different technique required to control the plasma current in fully non-inductive plasmas from that in ohmic heated (OH) ones. Therefore it is important to investigate the response of the plasma when the bulk heating and the tail heating are executed.

As the driven current by lower hybrid wave (LHW) is strongly affected by the ratio of phase velocity to the Dreicer velocity [1], the effective refractive index of the LHW along the magnetic field line, $\langle n_{//}\rangle$, was estimated from the analysis of the current ramp-up or –down experiment with the inductive assistance [2]. From the physical point of view, it is important to investigate the value of $\langle n_{//}\rangle$, because the value of $\langle n_{//}\rangle$ has direct relation to the current drive efficiency and the spectrum gap problem. The experimental result was also analyzed on the point of view of the inductive electric field and the recharging [2].

As for the current ramp-up in non inductive current drive plasmas, many experimental studies was done in the field of plasma start-up experiments without assistance of inductive current drive [3-7], because the plasma start-up without the assistance of center solenoid is able to provide a way of a cost-effective tokamak fusion reactor. The value of $\langle n_{//} \rangle$ in some start-up discharges was also estimated from many discharges [3]. Recently a simple model was proposed for the estimation of the current ramp-up rate [8]. According to this model, the current ramp-up rate can be expressed by $\mu_0 a^2/\eta(0)$, where a is a minor radius and $\eta(0)$ is the resistivity at the plasma center. This formula explains the experimental results in medium or large size tokamak, although the results in small tokamaks are not agreed [8].

Although the inductive plasmas or the start-up ones were studied in several tokamaks, the investigation of the current ramp-up in fully non-inductive plasmas is not enough. This paper shows that the experimental results in four types of plasma current ramp-up experiments on TRIAM-1M. In the section 2, the simple model for the current ramp-up is proposed, and the experimental results and its analysis are shown in section 3. The contents are summarized in section 4.

2. A simple model for the current ramp-up in non-inductive current drive plasma

Typical time evolutions of current ramp-up are shown in Fig. 1. The plasma was sustained by fully non-inductive LHCD and the additional LHCD was superimposed at 2sec. The plasma current ramps up and then it reached to steady state of the different plasma current from the previous one. At 2.35 sec, the transition to the ECD mode occurred and the plasma current ramps up again [9, 10]. It should note that the time evolutions of plasma current during the additional tail heating and the ECD mode were different. In the additional tail heating case, the plasma current increased exponentially with a time constant. While the time evolution of plasma current changed with a tangent-hyperbolic shape. This difference of the time evolution shows that the different mechanism works in each current ramp-up phase.

To investigated the details of the current ramp-up, a simple model is proposed as the followings. According to the Fisch's current drive theory, the power stored as the poloidal magnetic field in full LHCD plasmas was expressed under the ramp-up condition in full LHCD plsamas, $|E_t| \approx 0, E_t > 0$,

$$\frac{P_{el}}{P_{LH}} = V_L (I_p - \frac{V_L}{R_{sp}}) \approx \xi \left(\frac{v_{ph}}{v_r} \right)^2 \qquad (1),$$

$$v_r = \left(n_e e^3 \log\Lambda \big/ 4\pi\varepsilon_0^2 |E_t| m_e \right)^{1/2}$$

where V_L is the loop voltage on the last closed flux surface, R_{SP} is the Spitzer resistivity, ξ is a function of Z_{eff} and the effective power of LHW, η_{eff}, derived from the Fisch's current drive theory [1], v_{ph} ($=c/n_{//}$) is the phase velocity of the LHW, and E_t is the electric field to the toroidal direction induced by plasma current and poloidal field coils. In the case of full current drive plasmas, as the plasma current is sustained non-inductively, V_L in circular plasmas is expressed by,

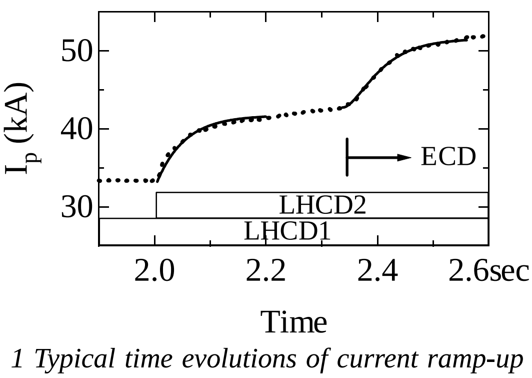

Fig. 1 Typical time evolutions of current ramp-up in full non-inductive LHCD plasmas. The base plasma was sustained by LHCD of 83 kW and an additional power for LHCD from 2 sec was 63kW. The phase differences of adjacent waveguides at the launcher are 90 degree in both LHCD. An ECD mode was triggered around 2.35 sec and the current ramp-up was observed. Two solid lines show the fitting curves derived form Eq. (2). The values of $\tau_{L/R}$ in the additional heating and the ECD mode are 49ms and 46ms, respectively. The values of τ in the additional heating and the ECD mode are 0 ms and 29ms, respectively.

$$V_L = -L\frac{\partial I_P}{\partial t}$$
$$L = \mu_0 R(\ln(8R/a) - 2) \quad (2).$$

Substituting Eq. (2) for Eq. (1) gives a differential equation for the time evolution of the plasma current as shown in the following,

$$\frac{\partial I}{\partial t} = -\frac{R_{sp}}{L}(I - I_M)$$
$$I_M = \frac{P_{LH}\xi(v_{ph})^2}{n_e R}\frac{2\varepsilon_0^2 m_e}{n_e e^3 \log\Lambda}.$$

This differential equation shows the plasma current ramps up exponentially with a time constant of L/R$_{SP}$ and it reaches to a constant value determined by the square of v_{ph}. Although ξ is a constant value determined by the ratio of the direct loss power of energetic electrons to the injected LHW power and Z_{eff}. On TRIAM-1M, the prompt loss of energetic electrons is not significant from the experimental observations as shown in section 3. Hence, the plasma current reaches to the value determined by the square of v_{ph}. This model sometimes gives an good agreement of the experimental results. However, this equation can not express the time evolution in the ECD mode as shown in Fig.1, which has the tangent-hypobaric shape. To explain the both time evolutions, a new model is proposed. It is assumed that the square of v_{ph} changes exponentially with a time constant, τ, which is the different from the time constant of L/R$_{SP}$. The differential quation is given by,

$$\frac{\partial I}{\partial t} = -\frac{R_{SP}}{L}\left(I - \left(1 - \exp\left(-\frac{t}{\tau}\right)\right)I_M\right),$$

and the solution can be expressed by,

$$I(t) = I_M\left(\frac{\tau_{L/R}\left(1-\exp\left(-\frac{t}{\tau_{L/R}}\right)\right) - \tau\left(1-\exp\left(-\frac{t}{\tau}\right)\right)}{\tau_{L/R} - \tau}\right) + I_0 \quad (2).$$
$$I_M = \frac{P_{LH}\xi\Delta(v_{ph})^2}{n_e R}\frac{2\varepsilon_0^2 m_e}{n_e e^3 \log\Lambda}$$

This equation can make a good fitting in both types of the time evolutions of the current ramp-up as shown Fig. 1.

3. The analysis of the experimental results

As above-mentioned, the value of ξ depends on the ratio of the power due to the direct loss of energetic electrons to the injected LHW power and Z_{eff}. The direct loss of energetic electrons in additional tail heating discharges with or without the transition to the ECD mode was measured as the thermal input on the movable limiter located in the low field side. The orbit of the energetic electrons deviates from the flux

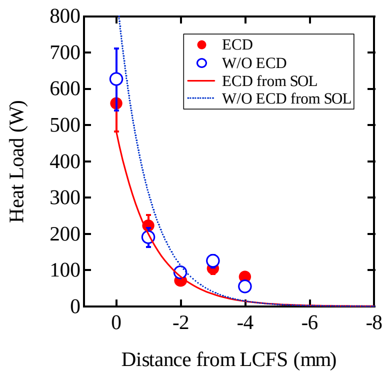

Fig.2: Heat load to the movable limiter (closed circles: ECD, open circles: non ECD) as the function of distance from the last closed flux surface (LCFS). Solid and dotted lines show the thermal input from the SOL plasma, respectively.

surface, therefore the energetic electrons driving plasma current attack to the movable limiter. The injected RF power is 65 kW and the estimated stored energy of tail electron is about 500 J. The result is shown in Fig. 2. The most thermal input to the movable limiter came from SOL plasma at both cases. The thermal input from energetic electrons cannot be detected. This shows that the loss of energetic electrons is quite small and the loss of energetic electrons does not play an essential role in the current ramp up. Therefore the value of ξ is a function of Z_{eff}. In the analysis of this paper, the value of Z_{eff} is assumed as 5.

The estimated value of τ in the ECD mode is 29ms in Fig. 1 and this indicates that the square of the effective v_{ph} increases with a time constant of 29ms. The physical mechanism of this increment is under consideration, however the increment of electron temperature is not suitable for the reason, because the time constant of increment of electron temperature (5-8 ms) does not agree with τ. The power dependence of τ is shown in Fig. 3. The value of $\tau_{L/R}$ in the additional heating is the constant of 50ms, which is comparable to $\tau_{L/R}$ of 100 eV. This temperature is comparable to the volume averaged electron temperature measured with Thomson scattering. The value of $\tau_{L/R}$ in the ECD mode increases with the increment of ion temperature as shown in Fig. 3(b), although the increment of ion temperature at the plasma center does not agree with the increase of $\tau_{L/R}$ completely. The values of τ are decreasing with the increase of P_{LH}. This shows that the time constant of the change of v_{ph}^2 depends on P_{LH} in the ECD mode. The effect of the additional ECH is also investigated. The time constant of $\tau_{L/R}$ (80ms) is longer than that in the additional tail heating case. This has no contradiction of the increment of electron temperature due to ECH. The value of τ is almost zero and this is different from the value of τ in the ECD mode. This is a proof that the increment of current drive efficiency is not caused by the increment of electron temperature in the ECD mode.

The dependence of $\langle n_{//} \rangle$ on $\Delta\phi$ is plotted in Fig. 4. The absolute values of $\langle n_{//} \rangle$ are derived from the fitting by use of Eq. (2). This tendency can be made sure from the measurement of the averaged energy of the energetic electrons derived from the HXR PHA measurement

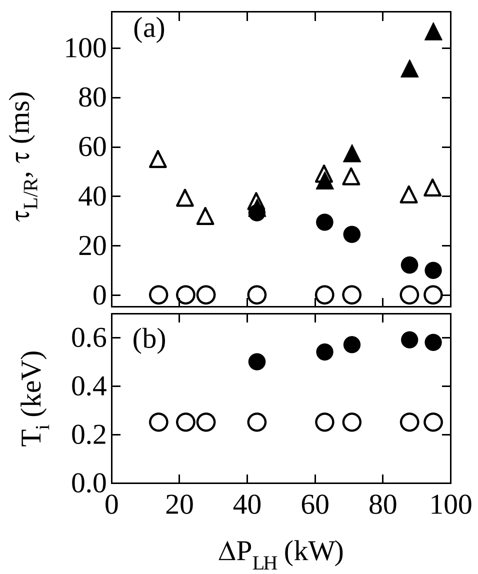

Fig. 3 Time constants expressed by Eq. (2) are plotted as the function of the additional P_{LH} (ΔP_{LH}). The base plasma was sustained by LHCD with P_{LH}=83kW. The values of $\tau_{L/R}$ in the additional heating (open triangles) and the ECD mode (closed triangles) and the values of τ in the additional heating (open circles) and the ECD mode (closed circles).

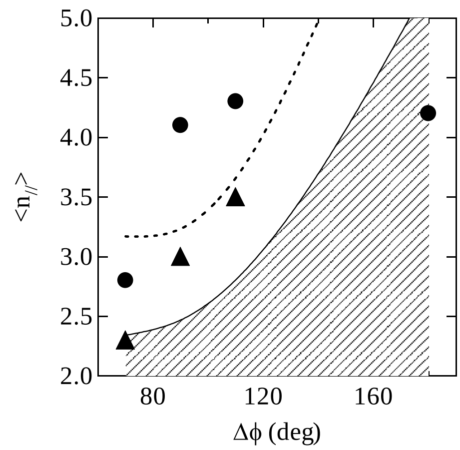

Fig. 4 The estimated $\langle n_{//} \rangle$ derived from the fitting by use of Eq. (2) as the function of the phase difference of the adjacent waveguide at the launcher. The base plasma is sustained by LHCD of $\Delta\phi$=90 deg. Closed circles show the value of $\langle n_{//} \rangle$ in the additional heating cases with LHCD of various $\Delta\phi$ and the closed triangles show that in the ECD cases. Hatched area shows that $n_{//}$ sheared by injected LHW and the dotted line shows the upper limit of the up-shifted value of $\langle n_{//} \rangle$.

along the vertical chord to the toroidal derection. In the ECD mode, the averaged energy of energetic electons becomes higher than that in non ECD plasma by 10%. The absolute value of the increment of the averaged energy does not agree with the predicted increment of the effective phase velocity. The absolute value of the increment of the effective phase velocity should be discussed by use of the tangential measurement of HXR PHA measurement to the toroidal field. The estimated $<n_{//}>$ are close to the value of $<n_{//}>$ of the injected LHW and the up-shifted $<n_{//}>$ predicted by the theor. The large spectrum gap still exists, because $n_{//}$ of the thermal velocity corresponds to 30. This shows that a physical mechanism works to fulfill the spectrum gap and electrons approaches to the resonance region of the LHW in the velocity space. The knock-on collision [11-13] is a candidate for the physical mechanism to fulfill the gap.

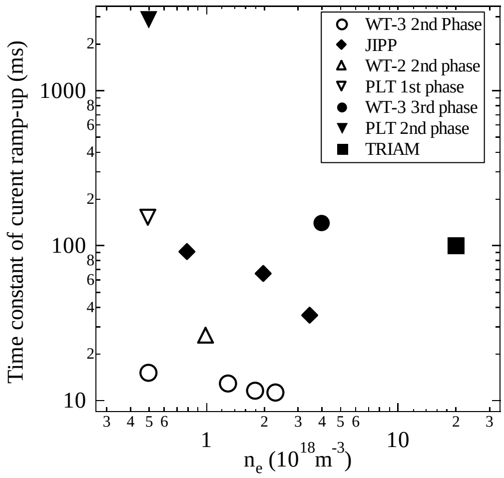

Fig. 4:The time constant of current ramp-up as the function of $\overline{n}_e$ in the start-up experiments by utilizing the combination of ECRH + LHCD in various tokamaks[3-6].

As for the current start-up experiments, The experimental regions are shown in Fig.4. Many experiments in various tokamaks were executed in low density region, and the experiment in the density of more than $1x10^{19}$ m^{-3} was carried out on only TRIAM-1M. After an initial plasma was produced by ECH of 170 GHz, the toroidal plasma current was ramped up and sustained up to longer than 30 sec by LHCD of 8.2 GHz without the inductive assistance. The cut-off density of O-mode in the frequency of 170 GHz corresponds to $3x10^{20}m^{-3}$, therefore high density plasmas could be obtained by fundamental ECH compared with previous start-up experiments in other tokamaks.

The time constants, $\tau_{L/R}$ and τ are 20 ms and 100ms, respectively. The value of $\tau_{L/R}$ corresponds to 30 eV. As the volume averaged electron temperature in start up phase is less than the full LHCD plasma in steady state phase because of low plasma current, this result is reasonable. The time constant of current ramp-up during start-up phase is dominated by the time constant of $<n_{//}>$. Thus, the problem of longer time constant of current ramp-up than that in steady full LHCD plasmas is explained by use of Eq. (2).

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