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# The plasma current control in the TRIAM-1M tokamak

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TRIAM-1M is a superconducting tokamak, the plasma is maintained by RF (radio frequency) wave completely without ohmic field in the steady-state operation. An active control of plasma current in fully non-inductive lower hybrid current drive (LHCD) plasmas on TRIAM-1M is demonstrated successfully for more than 1 min. A simple model to decide the PID (proportional integral and differential) control parameters based on secondary lower hybrid wave (LHW) is proposed. The PID parameters different from the prediction of the model prevent from maintaining plasma current well.

**Key words:** *LHCD, Current control, Tokamak, Steady-state operation*

## 1. Introduction

Usually, plasma current is initiated and controlled by ohmic heating in tokamaks operated in pulse mode, it is limited in long time duration because the increment of ohmic transformer flux is finite. So it is necessary to consider that the plasma would be controlled by non-inductive way for the steady state operation of tokamaks. The lower hybrid current drive (LHCD) is one of the most effective methods to sustain plasma current nowadays. Therefore the studies of the active control of the fully non-inductive plasma current by use of LHCD are fruitful to investigate the realization of steady state operation of tokamaks.

The LHCD was built for various experiments in tokamaks. For example, LHCD was used to control plasma current profile in JET [1] and JT-60U [2]. The non-inductive long time discharge has been sustained by LHCD in Tore Supra [1], JT-60U [3], HT-7 [4] and TRIAM-1M [5]. LHCD is only an assistant means in these experiments, plasma current is controlled by ohmic field mainly. It was studied to control full non-inductive plasma current by LHCD solely in TRIAM-1M.

TRIAM-1M($R_0$=0.8m, a × b=0.12m × 0.18m, B=8T) is a high toroidal magnetic field superconducting tokamak. Two kinds of LHCD systems have been installed. One is 2.45GHz, 50KW system with a klystron and a 4×1 grill launcher. Another is 8.2GHz, 200KW system with 8 klystrons and a 8×2 grill launcher. TRIAM-1M is a RF (radio frequency) tokamak, there is no ohmic field in its steady state operation, the plasma current is sustained by fully LHCD.

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## 2. The simple model for the plasma current control

In LHCD experiments, the average velocity of electrons is lower than the original wave phase velocity launched by LHCD grill launcher, there is a 'spectral gap' between original wave velocity and electron velocity. On TRIAM-1M, the large spectrum gap exists at any experiments because of low electron temperature and the systematic up-shift of LHW is not expected because of high aspect ratio [6]. As it is difficult to predict the foresight change of plasma current by use of feedback control of the injected power, we assume that the spectral gap was filled by up-shifted power, and resonant electrons were supplied to generate plasma current. A simple model [7] based on this secondary up-shifted wave was used to simulate the plasma current driven by LHCD. The secondary lower hybrid wave (LHW) is parameterized by $\eta_L$ and $w_L$ according to the reference 7, the absorption power density, driven current density and the current drive efficiency could be written as equation A2, A3 and A4 shown in appendix.

In TRIAM-1M case, contour plots of $\eta_L$ - $w_L$ space were shown in Fig.1 which were got from data with refractive index along the magnetic filed, $N_{//}$ = 1.3-2.9, volume averaged electron temperature, $\langle T_e \rangle$=0.65keV, lnΛ =17, $n_e$=2.5×$10^{19}$/$m^3$, $Z_{eff}$=3, R=0.84m, a=0.14m. The experimental results support the cross point which was marked by dots in Fig 1. It was found that $\eta_L$ ~ 5 and $w_L$ ~2.35, on the other hand, results were very sensitive to $w_L$, but not sensitive to $\eta_L$. When $\eta_L$ was fixed at 5, the further influence of $w_L$ parameter was shown in Fig.2. When a group of key parameter of $V_L$ was assumed, the absorption LHW power and corresponding driven current were also decided. The relation of plasma current and LHW power was illustrated through the model, which could be used to carry out real-time feedback control of plasma current. In real-time control, a point relative to $w_L$=2.35 could be set as *offset*, then a couple of current and power would be decided. When offset power was injected, the error of real current and offset current could be detected, and corresponding power difference also could be got from the curve of current and power in Fig.2. Since the curve is linear approximately, the control could be adopted to PID (proportional, integral and differential) control, the point relative to $w_L$=2.35 would be *offset,* and slope of the curve could be set as proportional gain $G_p$.

However, above PID control parameters were found on a given plasma parameter, so *offset* and $G_p$ should be changed when plasma parameters were altered such as temperature, density and $N_{//}$ etc. Then a group of control parameters would be derived.

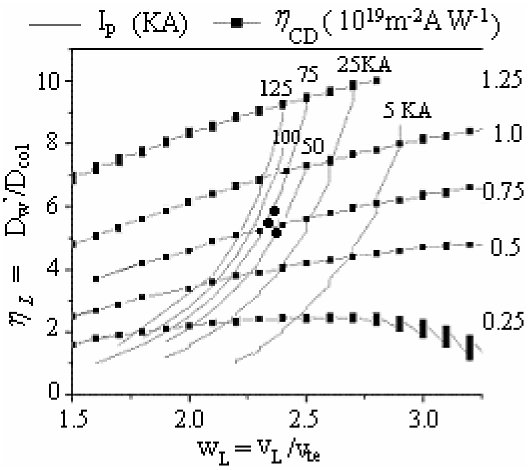


**Fig.1** Contour plots of $\eta_L$ - $W_L$ space in TRIAM-1M.

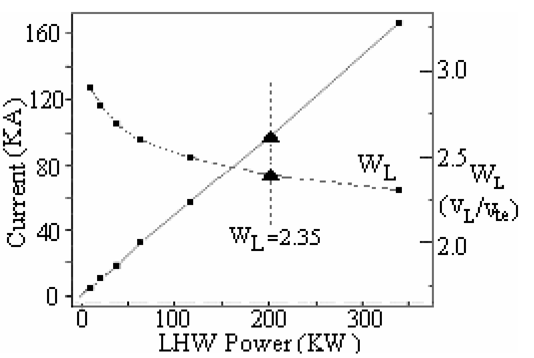


**Fig.2** The influence of $W_L$.

## 3. The feedback control parameters in TRIAM-1M

In full non-inductive plasma experiments of TRIAM-1M, the plasma parameter $n_e$ and plasma temperature are variable along with power adjustment of LHW. In order to simulate the relation of plasma current and LHW power through above-mentioned model, the power dependence of density and plasma temperature should be studied in advance.

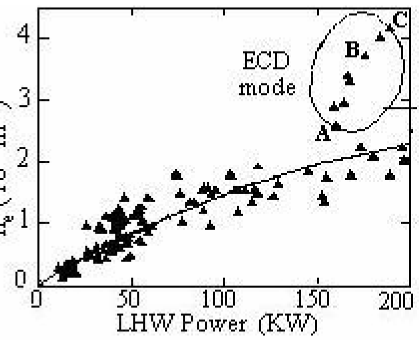


**Fig.3** Power dependence of density in TRIAM-1M.

### 3.1 Power dependence of density

In TRIAM-1M, the achieved density can be explained by a model derived from the balance between the energy confinement $\tau_E$, and current drive efficiency $\eta_{CD}$ of the LHCD scalings [8]. According to the reference 10, the relation of power and density could be deduced in L mode, it is illustrated by the curve on Fig.3, and it is also satisfied with experimental data marked by triangles.

But the power relation is different in enhanced current drive (ECD) mode [9] with L mode, the density is much higher as shown in Fig.3. Three points marked by A, B and C are selected to be considered.

### 3.2 Power dependence of plasma temperature

The experimental scaling of LHCD current drive efficiency is shown in Fig.4, the curve was fitted. The power dependence of plasma temperature shown as dot-dash curve in Fig.5 can be estimated by synthesizing the data of Fig.3, Fig.4 and the temperature dependence of current drive efficiency $\eta_{CD} = 12\langle T_e\rangle/(5+Z_{eff})$. Furthermore, experimental data, which are derived from ion temperature profile, marked by triangles also support this curve.

### 3.3 Control parameters

When power dependence of plasma density and temperature were considered in the model presented in Section 2, and other parameters like $N_{//}$ etc. were fixed, the relation of global current and LHW power was deduced at $W_L$~2.35 that is shown in Fig.6, corresponding $dI_p/dP$ was shown in Fig.7. Then the control parameter *offset* could be decided through the curve of Fig.6, and $G_p$ can be set as $dP/dI_p$ at each point of Fig.7 in plasma current feedback control experiment.

The control is built according to formula (A1) shown in appendix, $P$ is LHW power, $Ip$ is plasma current. Usually, the future state of plasma current drive can not be forecasted in advance, it will be decided by future situation, so $G_d$ (differential gain) which is used as forecast item of PID control is set as zero in real experiment. The control parameter *offset* and $G_p$ (proportional gain) can be got from Fig.6 and Fig.7. $G_i$ (integral gain) would be optimized to compensate the difference of real plasma and target plasma in experiments.

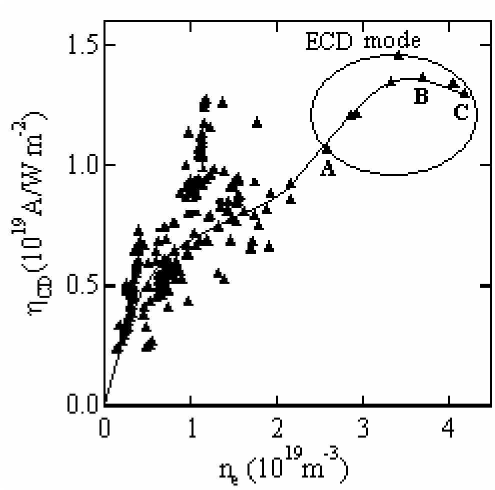


**Fig.4** Current drive efficiency scaling in TRIAM-1M.

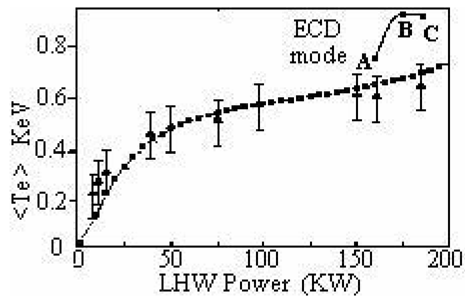


**Fig.5** Power dependence of plasma temperature in TRIAM-1M

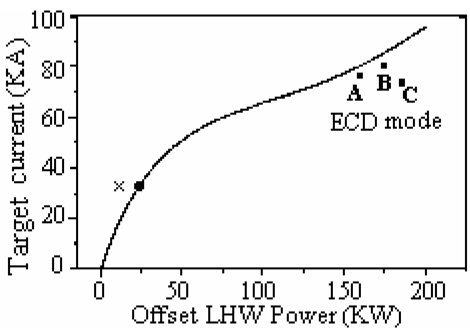


**Fig.6** *Offset* of PID control in TRIAM-1M.

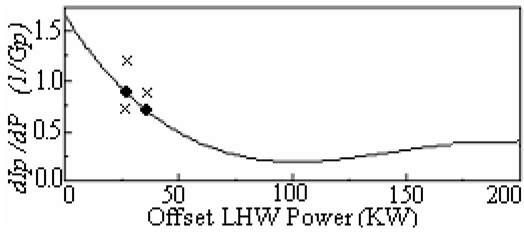


**Fig.7** $G_p$ of PID control in TRIAM-1M.

## 4. The result of active control experiments

The plasma current feedback experiments were carried out in TRIAM-1M, plasma was initiated by a small ohmic field power supply in original phase, subsequently it was sustained by LHW solely with feedback control, the plasma was operated in quasi-steady state.

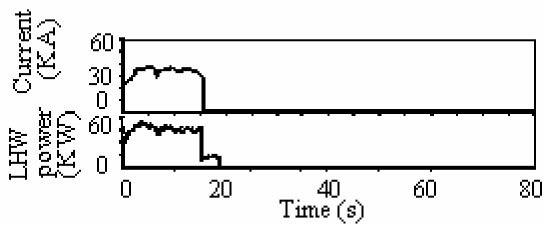


**Fig.8** The representative experiment waveform with open control in TRIAM-1M.

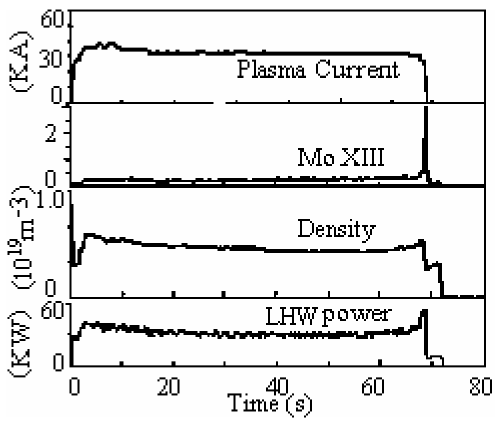


**Fig.9** The representative experiment waveform with feedback control in TRIAM-1M.

The representative experimental waveforms are shown in Fig.8 and Fig.9. The plasma is sustained by constant LHW with open control mode in Fig.8, but it is feedback controlled from 10s with same condition in Fig.9. Experiments show that the plasma current could be controlled by LHCD solely, the control is beneficial to obtain steady-state full non-inductive plasma. Moreover, the successful control parameters were marked by dots in Fig.6 and Fig.7, but it is failed to control plasma current commendably in the case of parameters marked by '×'. The plasma was found to be terminated by the production of the impurity during long pulse discharge in TRIAM-1M which keeps close relation with PWI (plasma wall interaction).

## 5. Conclusion

The feasibility of current feedback control was demonstrated in fully non-inductive plasma of TRIAM-1M. The experiments show that the method deducing control parameters through the simple model is successful, and the feedback control of plasma current is fruitful to obtain the steady-state plasma. The study was helpful for the control of future tokamak reactor without ohmic field.

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## Appendix:

$$P = offset + G_p \times \Delta Ip + G_i \times \int_{start-time}^{t} \Delta Ip + G_d \times {d\Delta Ip}/{dt} \quad \text{(A1)}$$

$$p = -\frac{n_e m v_{te}^2}{\tau_{st}\sqrt{\pi}} \exp(-w_L^2)\{\lambda^{1/\eta_t} \ln(w_2/w_1) + \frac{\eta_t}{2}(1-\lambda^{1/\eta_t})\} \quad \text{(A2)}$$

$$j = -\frac{e n_e v_{te}}{2\sqrt{\pi}} \exp(-w_L^2)\{\lambda^{1/\eta_t}(w_2^2 - w_1^2) - \frac{1 + w_L^2 - \lambda^{1/\eta_t}(1+w_1^2)}{1 - w_L^2/\eta_L}\} \quad \text{(A3)}$$

$$\eta_{CD} = \frac{n_e R I_{CD}}{P} = \frac{310}{\ln\Lambda}\frac{4}{(5+Z_{eff})} G(w_1, w_2, v_{te}, w_L, \eta_L) \quad \text{(A4)}$$

$$G(w_1, w_2, v_{te}, w_L, \eta_L) = \frac{v_{te}^2}{c^2} \frac{\lambda^{1/\eta_t}(w_2^2 - w_1^2) - [1 + w_L^2 - \lambda^{1/\eta_t}(1+w_1^2)]/[1 - w_L^2/\eta_L]}{\lambda^{1/\eta_t}\ln(w_2/w_1) + \frac{\eta_t}{2}(1-\lambda^{1/\eta_t})} \quad \text{(A5)}$$

$$w_k = v_k/v_{te}, \quad \lambda = w_L^2(1+\eta_L)/(w_L^2 + \eta w_1^2), \quad \eta_t = \eta_L / w_L^2, \quad \eta_L = D_w^{'}/D_{col}(V_L) \quad \text{and} \quad \tau_{st} = \tau_s(v_{te})$$

where $v_1$ and $v_2$ are the original minimum and maximum phase velocity of LHW, $v_L$ is the minimum velocity of the up-shifted spectrum of LHW, respectively. $D'_w$ and $D_{col}$ are the quasi-liner diffusion coefficient and the collisional coefficient.