Current Profile Control Study in Steady State Plasma of TRIAM-1M

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Abstract

Current profile control experiments have been carried out in TRIAM-1M by the combination of two lower hybrid waves (LHW's: 8.2 GHz and 2.45 GHz) with different spectra of parallel refractive index. In this case the current drive efficiency is improved by > 50% than those of 8.2GHz LHCD only and 2.45GHz LHCD only. This is attributed to the synergetic effect of the combination of the two LHW's. The internal inductance is reduced depending on the power of the 2.45GHz LHW. This means that the current profile changes from a peaked profile to a broad one, which is also supported by hard X-ray measurements. Moreover, the controlled current profile can be successfully sustained for about 2 orders in magnitude longer than the current diffusion time. The compatibility of the current profile control and the improved current drive efficiency is required for future fusion plasma. It is achieved by the combined LHCD in TRIAM-1M.

1. INTRODUCTION

In these years, various improved confinement modes have been investigated in many devices. Some of them can be obtained by the current profile control; for example, the negative shear configuration, based on the hollow current profile, can be formed by heating during the ramp-up phase of the plasma current[1]. However, the improved confinement formed by the above method is not available for steady-state plasma. In a future reactor, the plasma current and its profile should be controlled by a non-inductive method. The following subjects are key issues for the non-inductive current profile control; the improvement of current drive efficiency, η_{CD}, and steady-state controllability of the current profile.

The current drive efficiency should be improved for economical efficiency of the reactor. Although η_{CD} of LHCD is considered to be sufficient to the requirement for the reactor, it is estimated in the optimized condition; for example, the power deposition in the central region of the plasma or the current drive assisted by the OH electric field. In the negative shear configuration, η_{CD} would decrease because the RF power should be deposited in the outer region of the plasma for the hollow current profile. The current drive efficiency of the full current drive plasma is much lower than that of the plasma with the OH electric field [2,3].

It should be confirmed whether current profile, j(r), can be controlled and simultaneously η_{CD} can be improved during longer duration than the current diffusion time. In TRIAM-1M, the ultra long steady-state discharges have been already demonstrated [4]. Recently, the compatibility of the improved current drive efficiency and the steady-state controllability of the current profile has been investigated in the combined LHCD discharge.

2. EXPERIMENTS OF COMBINED LHCD DISCHARGES

The current profile control has been investigated by the combination of two lower hybrid waves (LHW's: 8.2 GHz and 2.45 GHz) in TRIAM-1M (R~0.8m, a×b=0.12m×0.18m, SUS wall, Mo limiter, Mo divertor plate). The experimental conditions are as follows: The toroidal magnetic field B_T=7T, line-averaged electron density $n_e \sim 1\times10^{19}m^{-3}$. The RF power of 8.2GHz is up to ~100kW and that of 2.45GHz is up to ~25kW. The phase difference between the adjacent wave guide, $\Delta\Phi$, of the 8.2GHz

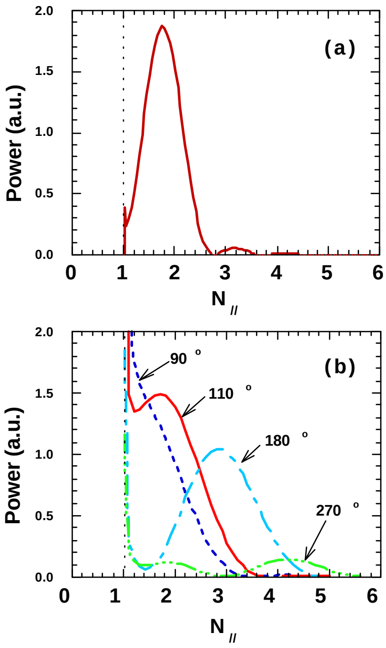

Fig.1. Power spectra of (a) 8.2GHz LHW and (b) 2.45GHz LHW

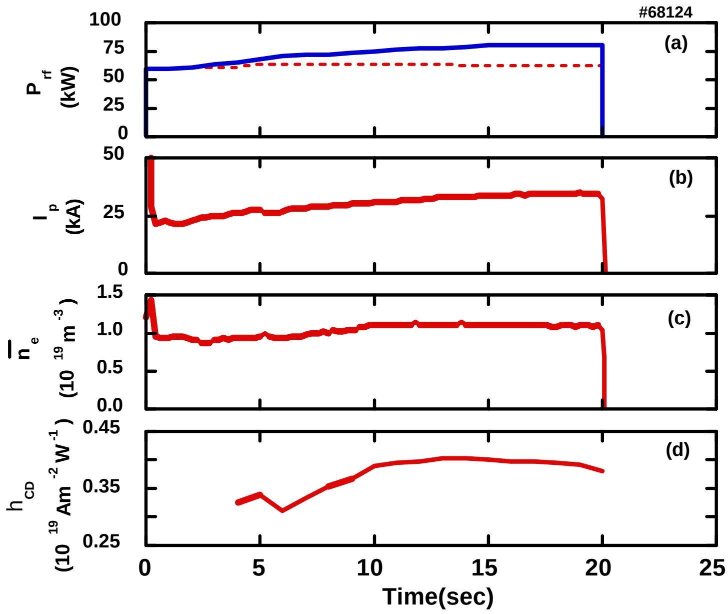

Fig.2. Typical waveforms of the combined LHCD. (a) The solid line shows the total power of 8.2GHz and 2.45GHz LHW's and the dashed line shows the power of the 8.2GHz LHW only, (b) the plasma current, (c) the line averaged electron density, (d) the current drive efficiency. ΔΦ of the 2.45GHz LHW is 110°.

LHW is 90° corresponding to the peak parallel refractive index, $N_{//}^{peak}$, of 1.8 and ΔΦ of the 2.45GHz LHW is 90° to 270° corresponding to $N_{//}^{peak}$ <4.2 as shown in Fig.1. The accessibility condition does not dominate the propagation of the 8.2GHz LHW because of high B_T. On the other hand, the 2.45GHz LHW with ΔΦ=90° may be affected by the accessibility condition because of small parallel refractive index.

Typical waveforms of the combined LHCD discharge in which the 2.45GHz LHW is superimposed on the 8.2GHz LHCD plasma are shown in Fig.2. The 2.45GHz LHW is superimposed from t=2s and its power is increased up to ~20kW at sufficiently slower rate than the current diffusion time ($\tau_{L/R}$~200ms). The plasma current and the electron density are increased by superimposing the 2.45GHz LHW. Because the fueling is controlled so as to keep the Hα line intensity of the central chord (i.e., the particle in-flux to the plasma) constant in this discharge. It should be indicated that the particle confinement is improved by superimposing the 2.45GHz LHW. The current drive efficiency is also increased by superimposing the 2.45GHz LHW. In the combination of the two kinds of LHW's with different spectra of parallel refractive index, the improvement of η_{CD} can also be expected because of the synergetic effect.

In order to evaluate the change in j(r), the internal inductance, l_i, the hard X-ray (HX) profile and its energy spectrum measured by an NaI scintillator array viewing a plasma vertically are utilized.

3. EXPERIMENTAL RESULTS

3.1. Improved current drive efficiency

The dependence of η_{CD} on P_{rf}(2.45GHz) and ΔΦ(2.45GHz) is examined. Figure 3 shows the dependence of η_{CD} of the full current drive discharge on the total RF power of 8.2GHz and 2.45GHz LHW's, where the reflected power is subtracted. The current drive efficiency of the combined LHCD is improved with P_{rf}(2.45GH). It is noted that η_{CD} is improved by a factor of ~1.5 times by superimposing the 2.45GHz LHW even though that of 8.2GHz LHCD alone is not improved by increasing P_{rf}(8.2GHz). The current drive efficiency has the maximum value of $0.41\times10^{19}Am^{-2}W^{-1}$ around ΔΦ=130° as shown in Fig.4. The deterioration of η_{CD} at lower $N_{//}^{peak}$ (ΔΦ=90°) may be due to the accessibility condition and that in

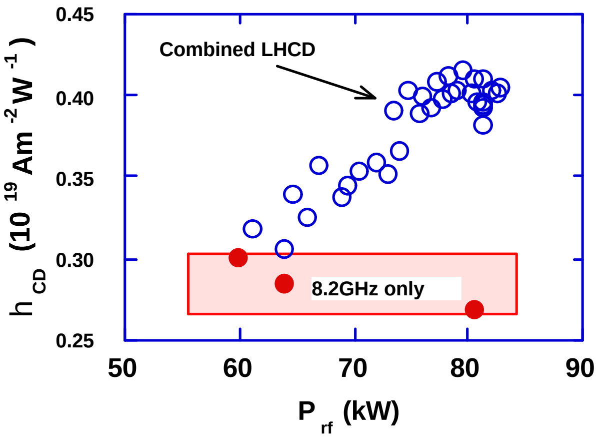

Fig.3. The dependence of η_{CD} on the total power of 8.2GHz and 2.45GHz LHW' s. Closed circles show η_{CD} of the 8.2GHz LHCD and open circles show η_{CD} of the combined LHCD.

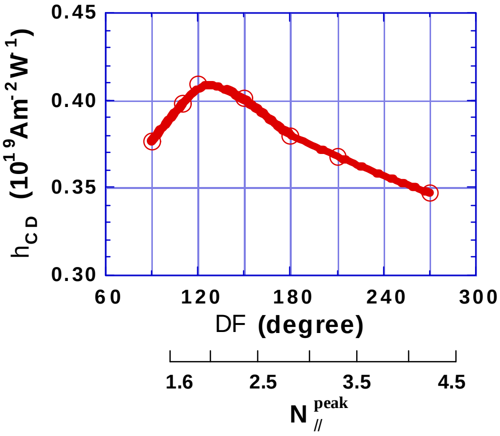

Fig.4. The dependence of η_{CD} of the combined LHCD on $\Delta\Phi$ of the 2.45GHz LHW. The power of 8.2GHz LHW is about 60kW and that of 2.45GHz LHW is about 20kW

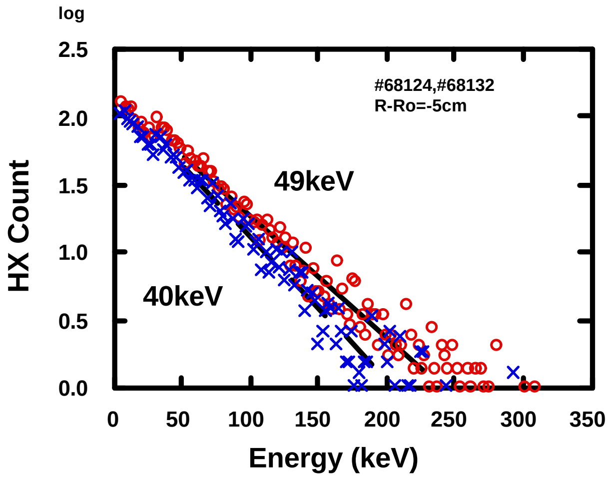

Fig.5. Spectra of the Hard X-ray emission. The crosses indicate the Hard X-ray counts of 8.2GHz LHCD only and open circles indicate that of the combined LHCD. $\Delta\Phi$ of the 2.45GHz LHW is 110^{o}.

higher $N_{//}^{peak}$ region may be due to the power deposition in the outer region of the plasma. However, It is noticed that η_{CD} of the combined LHCD ($90^{o}<\Delta\Phi<270^{o}$) is improved than those of 8.2GHz LHCD only and 2.45GHz LHCD only. This is attributed to the synergetic effect of the combination of the two LHW' s.

In the combined LHCD discharge, the spectrum of the HX intensity is different from that of the 8.2GHz LHCD only. The effective temperature of high energy electrons estimated from the slope in the spectrum of the HX intensity increases from 40keV to 49keV by superimposing the 2.45GHz LHW as shown in Fig.5. It is noted that the effective temperature does not increase by increasing the power of 8.2GHz LHW only. Moreover, the increase in the HX intensity in the higher energy region (E>150keV) becomes higher than that in the lower energy region (E<150keV). This suggests that the higher energy electrons are more accelerated by superimposing the 2.45GHz LHW and the local current density may be changed.

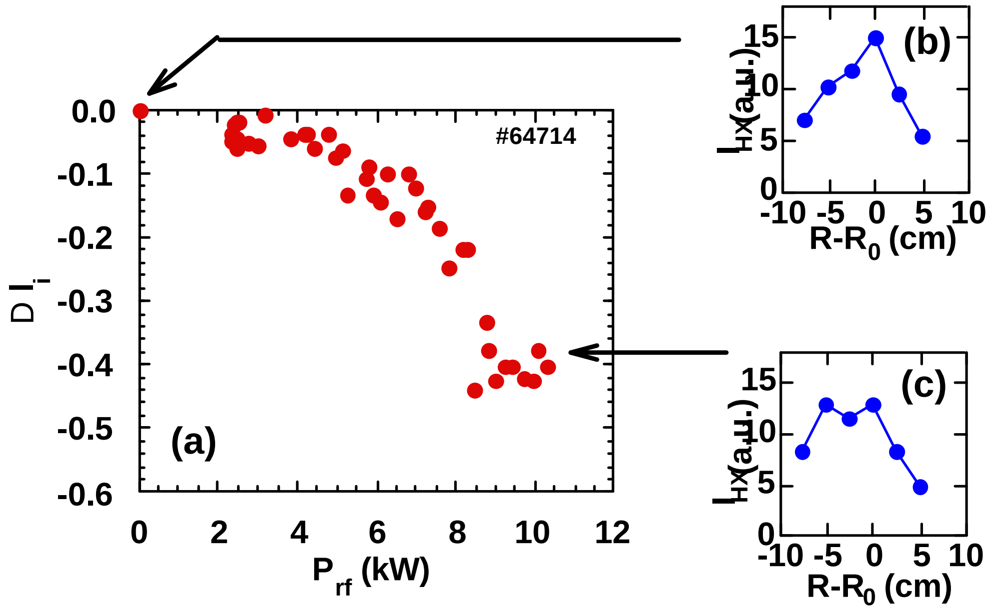

Fig.6. (a)The dependence of Δl_i on the power of 2.45GHz LHW superimposed on the 8.2GHz LHCD plasma. (b) and (c) The HX(E=80keV) intensity profiles at the timing indicated by the arrows.

3.2. Controllability of the current profile

The controllability of the current profile has been studied as a function of P_{rf}(2.45GHz). It is expected that the current profile can be controlled by combining two LHW's with different power spectra; that is, by changing the power deposition profile. As described above, the higher energy electrons can be accelerated. The local current density can be expected to be changed. The internal inductance, l_i, is estimated using the Shafranov Λ (=β_p+l_i/2-1) and the poloidal beta, β_p. The value of β_p can be evaluated by the following equation [5].

$$\beta_p = \beta_p^{bulk} + (1+\alpha) / (1-\alpha) \times C_t \times I_A(v) / I_{rf} \qquad (1)$$

Where I_A is the Alfven current and C_t is a numerical factor approximately equal to unity. The value α means the ratio of the backward current and the forward current, which is deduced using the power spectrum of the LHW. The value of β_p^{bulk} is calculated by the kinetic measurements of the density and the temperature. The dependence of the internal inductance Δl_i estimated by this method on P_{rf}(2.45GHz) is shown in Fig.6. The Δl_i means the difference from l_i just before superimposing the 2.45GHz LHW. It remarkably reduces with P_{rf}(2.45GHz). This suggests that the current profile becomes from a peaked one to a broad one depending on P_{rf}(2.45GHz). The profiles of HX intensity shown in Figs.6(b) and (c) are consistent with j(r) broadening deduced from Δl_i.

Moreover, the controlled current profile can be successfully sustained for about 2 orders in magnitude longer than the current diffusion time. The profile sometimes becomes concave. This indicates that the current profile can be controlled in the steady-state condition by the combination of LHW’ s.

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