New Transition Phenomena in a Long Discharge on TRIAM-1M

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Abstract Enhancement of current drive (ECD) efficiency mode, which is characterized by the spontaneous increase of current drive efficiency, η_{CD}, from 0.3-0.4 x 10^{19} A/Wm^{-2} to 0.7-1.0 x 10^{19} A/Wm^{-2}, is observed in long pure lower hybrid current drive (LHCD) plasmas on TRIAM-1M. The energy confinement time is also improved due to the increase of line averaged electron density, ion and electron temperatures. The current drive efficiency is proportional to the electron density. The transition to ECD mode occurs at a critical density, which slightly depends on the refractive index to the toroidal direction, $N_{//}$ of the injected wave.

1. Introduction

Steady state operation is an important requirement for nuclear fusion research. Development of reliable current drive method is an indispensable issue to realize a cost-effective tokamak fusion reactor. Lower hybrid current drive (LHCD) is one of most reliable current drive method for sustaining the plasma current in tokamak devices [1]. A maximum non-inductive current drive efficiency up to 3x10^{19} A/Wm^{-2} was obtained on JT-60 [2]. In the view of steady state operation of tokamak, LHCD has been contributed as shown in a 2 hours discharge obtained on TRIAM-1M [3]. Recently, LHCD works successfully in making the high performance plasma through current profile control. A lower hybrid enhanced performance (LHEP) in Tore Supra had been obtained for 2 min [4]. Moreover the combination with a preheated NBI plasma at the current ramp-up phase could sustain a reversed magnetic shear configuration for 7.5 s [5] and an ELM-free H-mode was also demonstrated by the combination of ohmic heating (OH) and LHCD in JT-60U [6]. The effective ion heating and the formation of transport barrier for 1 min were observed in low density LHCD plasmas on TRIAM-1M.

In spite of many successful results coming from LHCD experiments, almost experiments have been executed in transient time scale except TRIAM-1M and Tore Supra. The study about the feature of plasmas in long discharges is quite poor and the finding and the understanding of new phenomena in long discharges is important for fusion research. A newly transition phenomena is observed in a long discharge on TRIAM-1M. The transition occurs in medium density region. In this paper, the details of the transition are described in section 2 and the brief discussion about the possible mechanism of the transition is executed in section 3. The contents of this paper are summarized in section 4.

2. Experimental results

TRIAM-1M is a high field non-circular tokamak with 16 superconducting toroidal coils made by Nb_3Sn. Their coils can produce high toroidal magnetic field up to 8 T at the plasma centre. Two 8.2GHz LHCD systems (maximum power in one system = 200kW, 8x2 grill type launcher) and a 2.45 GHz LHCD one (maximum power = 50kW, 4x1 grill type launcher) are installed. The total power up to 450kW is available to LHCD. An open diverter made by Molybdenum is installed on a lower side and three poloidal limiters made by Molybdenum are also installed. The experiments in this paper are executed in limiter discharges. The phase difference between adjacent wave guides at the launcher of one system, $\Delta\phi$, adjusts to 90 degree

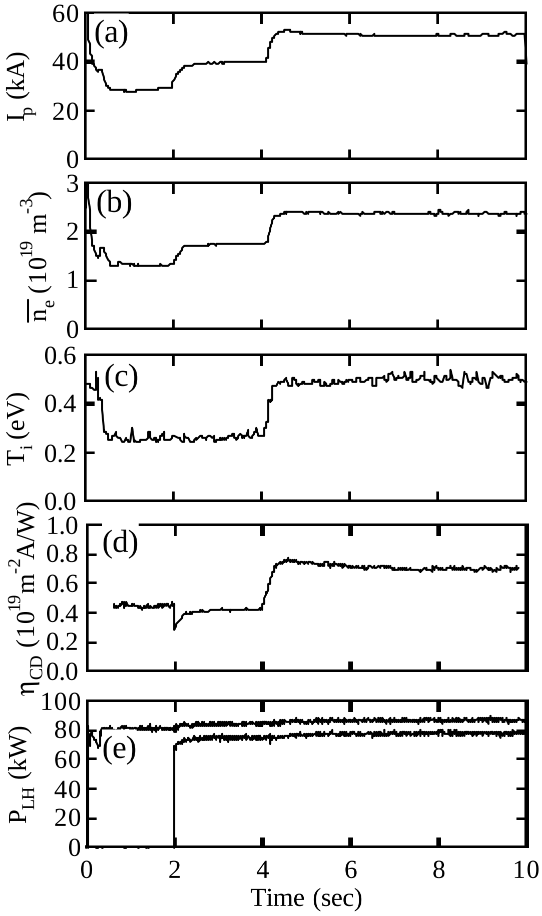


Fig. 1 The typical waveforms of (a) plasma current, I_p, (b) line-averaged electron density, $\overline{n}_e$, (c) ion temperature, T_i, (d) *current drive efficiency defined by* $\eta_{CD} = \dfrac{I_p \overline{n}_e R}{P_{LH}}$ *, and (e) injected lower-hybrid wave power, P_{LH} with ECD. The injected power is 80kW (Δφ=90 degree) for the sustaining of the plasma and the additional power from 2 sec is 75 kW (Δφ=110 degree). The ECD mode appears from 4 sec spontaneously*

at any time and that in another system sometimes changes from 70 to 270 degree for investigation of Δφ dependence.

A transition is observed in a long discharge sustained by two 8.2GHz LHCD systems. The typical waveforms including a transition are shown in Fig. 1. The plasma of $\overline{n_e}$ ~$1.4\text{x}10^{19}$m^{-3}, T_e ~ 0.5keV, T_i ~ 0.3keV, η_{CD}~0.35-0.45x10^{19} A/Wm^{-2}, and q~15 is sustained by an 8.2 GHz LHCD with P_{LH}~ 80kW up to 2sec. Subsequently, the additional P_{LH} is injected into the plasma by means of another 8.2 GHz LHCD system with Δφ=110 degree from 2 sec to 4sec. After the addition of P_{LH}, the plasma current increases up to 40kA and $\overline{n_e}$ also increases, although η_{CD} and T_i do not change. After 2 sec from the addition of P_{LH}, I_p and $\overline{n_e}$ are enhanced spontaneously. It should be noted that 2 second is significantly longer than the current diffusion time, ($\tau_{L/R}$~0.2 sec). T_i is also enhanced from 0.24 to 0.48 keV. The value of η_{CD} reaches up to 0.7x10^{19} A/Wm^{-2} at T_e=0.8keV, which is about double as magnitude of that predicted by the JT-60 scaling [8]. The energy confinement time, τ_E, is improved from 5ms to 8 ms, ($H_{ITER\text{-}89P}$ = 0.9->1.4), which are estimated by the stored energy measured with the diamagnetic loop and net RF input power, P_{LH}. This indicates that the transition in η_{CD} is accompanied with the improvement of energy confinement.

The time evolution of T_e also investigated by means of Thomson scattering by shot as shown in Fig. 2. Although the error bar is not so small, T_e significantly increases from 0.5 to 0.8 keV due to the appearance of ECD mode.

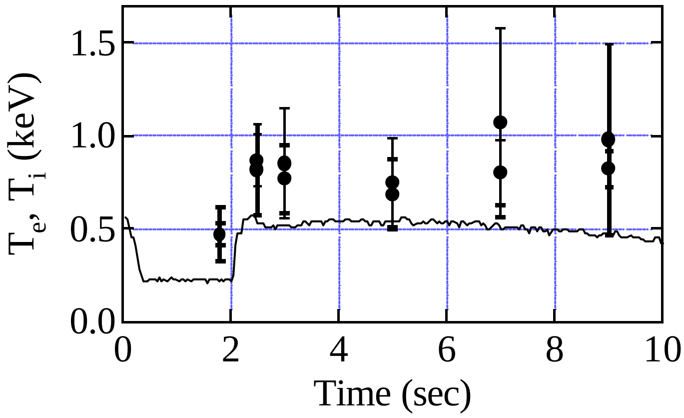
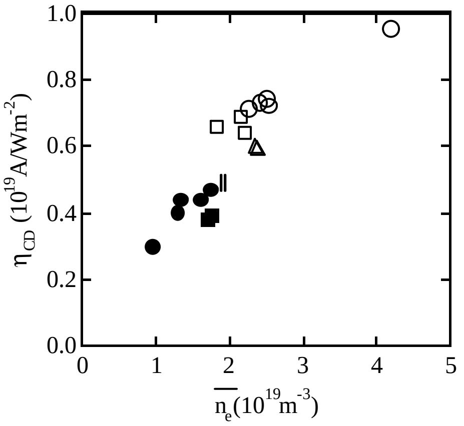


Fig. 2 Time evolutions of T_e and T_i at the plasma centre with ECD. The transition to ECD occurs at 2 sec. T_i measured with neutral particle analyzer.

The most typical observation in ECD mode appears in the similarity of the waveforms of I_p and $\bar{n}_e$. According to the theoretical prediction, the increasing of density leads to the reduction of I_p because of the increase of the drag in the momentum space. Figure 3 shows η_{CD} as the function of $\bar{n}_e$. As shown in Fig.3, η_{CD} is proportional to $\bar{n}_e$ in the wide range of $\bar{n}_e$. Moreover, this dependence of η_{CD} can be shown in both ECD and no ECD plasmas on TRIAM-1M.

The time scale of the transition to the ECD mode should be also investigated. The duration required from the start of the transition to the end in ion temperature is about 20 ms, which is comparable to 2~3 τ_E. It takes about 0.2 sec to saturate the plasma current and density, which corresponds to the current diffusion time. The delay time to the start of ECD mode from the injection of the additional power is significantly longer than the current diffusion time. Before the transition, the plasma position, the reflected LHW power from the plasma and Shafranov Λ seems to be in the steady state. However, $\bar{n}_e$ and I_p gradually increase. In TRIAM-1M, the signal of H_α keeps constant to control the density in a feedback manner. Therefore the increase of density in long discharges means to the improvement of particle confinement time. Although it is difficult to identify the cause of this long time scale change of plasma parameters, the time scale is comparable to the change of the hydrogen recycling ratio [7]. This delay time sometimes reaches over 10 $\tau_{L/R}$. The delay time slightly depends on P_{LH} and $\Delta\phi$. The lower power and the larger $\Delta\phi$ bring to the longer delay time.

The transition to ECD has a threshold in $\bar{n}_e$. The critical $\bar{n}_e$ just before the transition is plotted as the function of LH power as shown in Fig.4. Many data are close to 1.8×10^{19}m^{-3} in spite of various wave conditions. In the case of $\Delta\phi$=90+70 degree, the threshold density is slightly lower than that in $\Delta\phi$=90 degree. Moreover in the case of $\Delta\phi$=90+180 degree, the transition is not observed up to 1.95×10^{19}m^{-3}. In the case of $\Delta\phi$=90, power spectrum of injected LHW peaks at the refractive index to the toroidal direction, $N_{//}$=1.8, while in the case of $\Delta\phi$=180 degree, the peak exists in $N_{//}$=3. This suggests that the high $N_{//}$ component does not play an effective role in the transition to ECD.



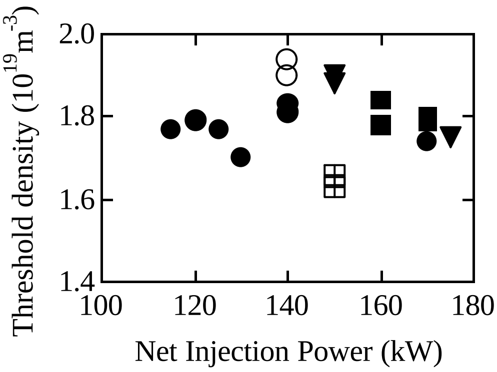


Fig. 3 The current drive efficiency is plotted as the function of $\overline{n}_e$. The plotted data include the plasma with both ECD (open marks: circles, $\Delta\phi$=90 degree, triangles $\Delta\phi$=90+70 degree, squares, $\Delta\phi$=90+110 degree) and no ECD (closed marks: circles, $\Delta\phi$=90 degree, squares $\Delta\phi$=90+110 degree, rhombus $\Delta\phi$=90+180 degree).

Fig. 4 Threshold $\overline{n}_e$ is plotted as the function of L_{LH}. Closed circles ($\Delta\phi$=90degree, 7T), closed squares ($\Delta\phi$=90+110degree, 7T), closed triangles ($\Delta\phi$=90degree, 6T), open squares ($\Delta\phi$=90+70 degree, 7T), are plotted. In $\Delta\phi$=90+180 degree (open circles), although the transition to ECD does not occur, the data are plotted as the reference.

3. Discussion

From the theoretical point of view, the increasing of T_e is not significant in the enhancement of η_{CD} on TRIAM-1M, because the large spectrum gap exists even in ECD mode. The spectrum gap is the difference between the phase velocities of the waves and the thermal velocity of bulk electrons. If the gap is too much, the wave and the electrons cannot interact, where the lower hybrid wave (LHW) cannot drive the plasma current. The large gap should be bridged to sustain significant current. However the increment of T_e in the ECD mode is not enough to fill the gap. Conventional models [8-10] to fill the gap expects that the phase velocity parallel to the magnetic field of the launched LHW becomes slower along the propagating path into the plasma, i.e., in other words $N_{//}$ shifts upwards in the plasma. On TRIAM-1M, the up shifting of $N_{//}$ does not expect due to high aspect ratio [9]. Moreover, the full wave calculation was also carried out, however the significant up shifting of $N_{//}$ could not expect in TRIAM-1M [10]. If the number of gap electrons plays an essential role in the current drive efficiency, the additional injection of LHW with high $N_{//}$ should be effective in the enhancement of η_{CD}. However, the additional injection of LHW with high $N_{//}$ component is not effective in making ECD mode. These indicate that the increasing of T_e is not main reason of the appearance of ECD mode.

Recently knock-on collision works significantly on the production of avalanche of energetic electrons at the plasma disruptions [11-13]. If knock-on collision works effectively, the spectrum gap may be filled, because energetic electrons can be made from bulk electrons by means of knock-on collision directly. 1-D Fokker-Planck equation is derived from the bounce averaged gyro kinetic relativistic Fokker-Planck equation, where the pitch angle scattering and the toroidal effect are ignored. Driven current and current drive efficiency are estimated by means of the simple 1-D Fokker-Planck equation. When the knock-on collision is taken into consideration, plasma current can be driven even in the case of the large spectrum gap. However, it is difficult to demonstrate the increase of the plasma current with the density. Although the knock-on collision is a possibility to fill the spectrum gap and to drive the transition, the future study is required.

4. Summary

The spontaneous increase of current drive efficiency, η_{CD}, from 0.3-0.4 x 10^{19} A/Wm^{-2} to 0.7-1.0 x 10^{19} A/Wm^{-2}, is observed in a long pure LHCD discharge on TRIAM-1M. The energy confinement time, τ_E, is improved from 5ms to 8 ms, ($H_{ITER\text{-}89P}$ = 0.9->1.4). The value of η_{CD} is proportional to $\bar{n}_e$ in the wide range of $\bar{n}_e$. The transition to ECD mode occurs at a critical density, which slightly depends on the $N_{//}$ spectrum of the injected LHW.

The increase of T_e is not enough to fill the large spectrum gap and does not play an essential role in the transition to ECD mode. The knock-on collision is investigated for the possibility of the mechanism of LHCD on TRIAM-1M. However, according to the simple calculation based on the effect of the knock-on collision, the density dependence of η_{CD} cannot be demonstrated. The investigation of the mechanism of ECD is the future work.

5. References

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