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Measurement of prompt loss of energetic electrons in a long LHCD discharge on TRIAM-1M

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On TRIAM-1M, spontaneous enhancement of non-inductive current drive efficiency (ECD) has been observed in full lower hybrid current drive plasmas. It is predicted theoretically that the prompt loss of passing energetic electrons has a significant effect to current drive efficiency in small size tokamaks. As the orbit of the energetic electrons deviates from flux surface, the energetic electrons driving plasma current attack to the limiter in the low field side. Therefore the absolute value of the power due to the prompt loss of energetic electrons can be measured as the thermal input on the limiter located in the low field side of the plasma. The measured heat flux in both ECD and non ECD plasmas is less than 1% of the injected microwave and most of the thermal input can be explained quantitatively by that from SOL plasma. This indicates that the loss of energetic electrons does not play a significant role in the enhancement of current drive efficiency in the ECD mode.

Introduction

Steady state operation of tokamaks is a key issue for the realization of cost-effective fusion power plant. Therefore, the efficiency of non-inductive current drive is still crucial point. As even in burning plasmas, momentum input to drive a part of plasma current will be required, the improvement of current drive efficiency is required.

TRIAM-1M (R=0.8m, a x b = 0.12 x 0.18m, B_t<8T), which has 16 superconducting toroidal coils made of Nb_3Sn to produce 8T at plasma center, is positively tackled with the study of RF current drive, plasma surface interaction (PSI), and confinement improvement [1]. Spontaneous enhancement of current drive efficiency (ECD) was observed in long duration plasmas sustained fully by 8.2 GHz lower hybrid current drive (LHCD) [2-4]. The energy confinement time estimated by the stored energy measured with the diamagnetic loop and net RF input power has been also improved. The current drive efficiency may be enhanced by the increment of electron temperature [5], and the reduction of loss of energetic electrons [6].

The prompt loss of passing energetic electrons is able to play an essential role in the absolute value of current drive efficiency [6]. The observed current drive efficiency is about one-tenth order of that predicted theoretically even in ECD mode. Therefore the confinement time of energetic electrons, τ_F, should be shorter than a thausand times of the amplitude of bulk collision time, (τ_B~ 2μs), that is, τ_F should be shorter than a few ms. The estimated stored energy of the energetic electrons is 200-500 J in typical LHCD plasma sustained by 8.2GHz LHCD with the power of 120kW. When the confinement time of energetic electrons is a few ms, almost of injected RF power should be lost by prompt loss of energetic electrons. In fact, one third of the injected RF power was lost by the prompt loss in a small tokamak, WT-3 [7], therefore the absolute measurement of the prompt loss of energetic electrons is important for understanding the absolute value of the efficiency of LHCD. In this paper, the method and the result of the measurement of the absolute value of prompt loss of energetic electrons are shown.

Experimental Apparatus

Lower hybrid wave (LHW) and electron cyclotorn wave (ECW) are available as additional heating sources on TRIAM-1M. Two kinds of LHW, whose frequencies are 8.2 GHz and 2.45 GHz, are available. As for LHW of 8.2 GHz, two lunching systems, whose anttenna is composed of an 8 x 2 grill type waveguide array, are installed, therefore the variation of the lunching power spectrum is flexible. Its maximum power is 400 kW (200 kW x 2). As for LHW of 2.45 GHz, a lunching system (4 x 1 grill type waveguide array, 50kW) is also installed. The ECW of 170 GHz up to 200 kW is lunched as O-mode for the production of plasma and electron cyclotron heating (ECH).

The orbit of the energetic electrons deviates from flux surface, therefore the energetic electrons driving plasma current attack to a limiter on the low field side. When a limiter is located apart from the last closed flux surface (LCFS) by 1cm, a part of energetic electrons shown in Fig. 1 does not reach to the limiter, therefore the profile of the heat load may bring us to the information about the energy and pitch angle distribution of loss electrons. A limiter is movable in the radial direction, thus the radial profile of heat flux of the energetic electrons on the movable limiter can be measured.

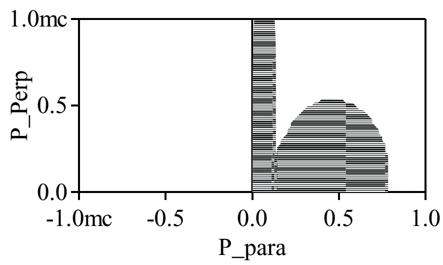

Fig. 1. A shadow area shows the region in the momentum space, where the energetic particles does not reach to the movable limiter located apart from LCFS by 1cm.

The heat flux has been measured as the increment of temperature of a limiter head made of copper covered with Mo. Moreover thermal input from SOL plasma should be monitored. A Langmuire probe has been installed on the limiter head to investigate the parameters of SOL plasma.

The absolute value of the prompt loss of energetic electrons was measured as the thermal input on the movable limiter located in the low field side of the plasma. The limiter head is composed of the copper block and the covers made of the molybdenum. The total thermal input on the movable limiter was monitored by the thermocouple put between the copper block and the molybdenum cover. The temperature of the limiter head measured with the thermocouple has the good sensitivity to the thermal input. The limiter head was cooled by water. The absolute value of the total thermal input on the limiter head was calibrated by the total amount of heat load measured by increment of water temperature in a LHCD discharge for 40sec. As the result, the increment of the temperature at the limiter head of 7 degree is corresponding to the total thermal input of 290 J on the movable limiter.

Finally, to make sure the linearity of this measurement, the thermal inputs are plotted as the function of the duration of discharges as shown in Fig.2. This result shows the linearity of the measurement seems to be good. The offset value of the increment of the temperature in Fig.2 corresponds to the heat load at the ohmic phase.

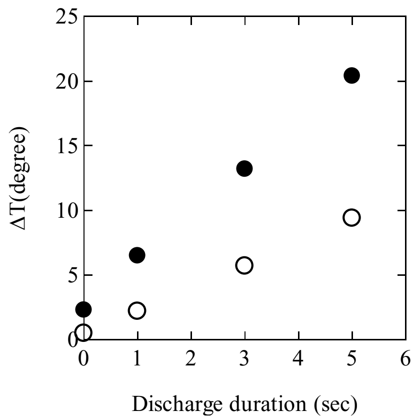

Fig. 2 The increment of the temperature at the head of the movable limiter on the position of 3mm from LCFS (closed circles) and 5mm open circles is plotted as the function of pulse duration.

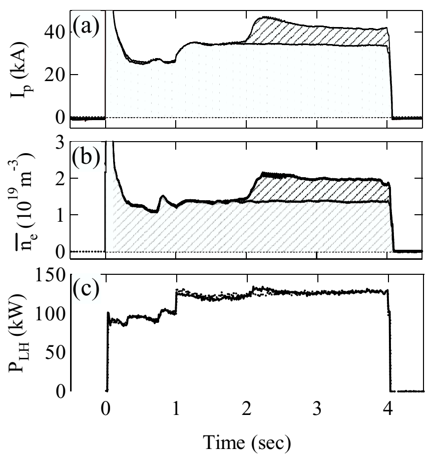

Fig. 3 Typical waveforms of (a) Ip, (b) $\overline{n}_e$, and (c) injected power in ECD and non ECD discharges. Hatch regions show that the increment of (a) Ip and (b) $\overline{n}_e$ due to transition to the ECD mode.

Experimental results

In Fig. 3, typical time evolutions of plasma parameters in ECD and non ECD plasmas are shown. The transition to the ECD mode takes place around 2 sec and then plasma current, density increases. Spontaneous enhancement of current drive efficiency from 0.25 x 10^{19} A/Wm^{-2} to 0.6 x 10^{19} A/Wm^{-2} has been observed in long 8.2 GHz full LHCD plasma. It should be noted that the injected LHW power in both cases is the same (P_{LH}=120kW) as shown in Fig. 2(c). This indicates that the injected power of 120 kW is quite close to the threshold power of the transition to the ECD mode [2, 3]. The energy confinement time, τ_E, is improved from 5ms to 8 ms, ($H_{ITER-89P}$ = 0.9->1.4), which are estimated by the stored energy measured with the diamagnetic loop and net RF input power, P_{LH}. The value of T_e measured by Thomson scattering also increases from 0.5 to 0.8 keV [2, 3]. A flux surface in both ECD and non ECD mode reconstructed by use of the magnetic data measured with a magnetic probe array does not change so much, especially the position of LCFS is the same within the error of the measurement.

The measurement of the prompt loss of energetic electrons was carried out in the plasma sustained by injected LHW power of 120 kW and the estimated stored energy of energetic electron was 200-500 J in the kinetic calculation. The measured heat flux is about 0.5 kW and most of the thermal input to the movable limiter comes from SOL plasma as shown in Fig. 4. The thermal input from energetic electrons may be negligible compared with the value predicted theoretically as described above. The situation is the same in ECD or non ECD plasmas. This shows that the loss of energetic electrons is quite small and the loss of energetic electrons does not play a significant role in the enhancement of current drive efficiency. Other mechanisms are required to understand the ECD mode. We speculate that the spectrum gap has the strong relation to the ECD mode.

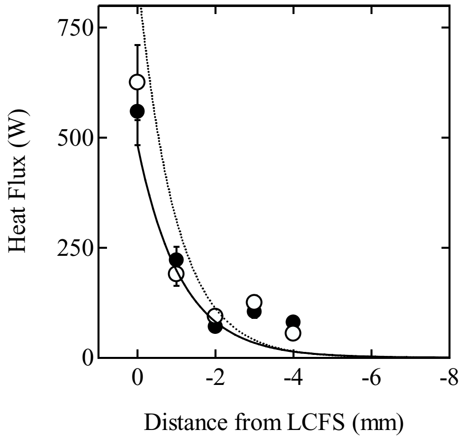

Fig.4. Heat load to the movable limiter (closed circles: ECD, open circles: non ECD) as the function of distance from last closed flux surface (LCFS). Solid and dotted lines show the thermal input from the SOL plasma, respectively.

Acknowledgements

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