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# Calorimetric measurement of heat load in full non-inductive LHCD plasmas on TRIAM-1M

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**Abstract**

Calorimetric measurements using the temperature increment of cooling-water were carried out to estimate the heat load distribution on the plasma facing components (PFCs) in the limiter discharges on TRIAM-1M. Line averaged electron density, $n_e$, and LH power, $P_{LH}$, dependences of the heat load on PFCs were measured. The heat load on the limiters was proportional to $n_e^{1.5}$ in the range of $n_e = 0.2–1.0 \times 10^{19}\ \mathrm{m}^{-3}$ and $P_{LH}^1$ in the range of $P_{LH} = 0.005–0.09$ MW. For $P_{LH} > 0.1$ MW, the plasma transition to an enhanced current drive (ECD) mode appeared and the $n_e$ dependences on the heat load on the limiter moderated. This indicates that the heat flux to scrape-off layer (SOL) region was reduced due to the improvement of the plasma confinement. The up–down asymmetry of the heat load on the vacuum vessel was enhanced in the ECD mode, which may be caused by the increasing of the direct loss of energetic electrons.


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*Keywords:* Calorimetry; First wall; Power balance; Steady State; TRIAM-1M

## 1. Introduction

The steady state operation is one of key issues to realize the magnetic fusion power plants. To execute the steady state operation of tokamak, many non-inductive current drive methods were developed and a more than 5 h discharge could be obtained using lower hybrid current drive (LHCD) on TRIAM-1M [1] in very low power region (<0.02 MW). In TRIAM-1M, it is difficult to make a steady state discharge in high power region due to the cooling capability of the plasma facing components (PFCs). In Tore Supra, the improved cooling capability enables the longer discharges [2]. The main difference between a pulsed operation and a steady one is the handling of the heat and the particles. Although the huge heat load comes from plasma in the pulsed operation, the condition of the PFCs does not affect the performance of the plasma so much. On the contrary in the steady state

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operation, plasma wall interactions (PWI) play an essential role in the maintenance of the plasmas. It is significant to investigate the heat load distribution on the PFCs in steady state operation of tokamaks. Moreover the plasma parameter dependences on the distribution of the heat load are also important in order to extrapolate the results to large devices such as ITER.

Calorimetric measurements using the temperature increment of cooling-water were carried out to estimate the heat load distribution on the PFCs in the limiter discharges on Tore Supra [3] and TRIAM-1M [4,5]. The total amount of the power estimated by calorimetric measurement was coincident with the injected lower hybrid power within 5% in steady state condition [4,5], where the temperature of the cooling water becomes steady. The distributions of the heat load are the following: 20% to the limiter, 80% to the vacuum vessel including divertor plates. In the pulsed discharges, the measured heat load on the limiter can be estimated as well as in steady state condition, however the measured heat load on the vacuum vessel is less than that in steady state condition. The missing power may play a role in the mild increase of the temperature of the vacuum vessel.

## 2. Experimental apparatus

TRIAM-1M is a high field non-circular tokamak with 16 superconducting toroidal coils made from $Nb_3Sn$. These coils can produce high toroidal magnetic field up to 8 T at the plasma centre. Two 8.2 GHz LHCD systems (maximum power in one system = 200 kW, 8 × 2 grill type launcher) and a 2.45 GHz LHCD one (maximum power = 50 kW, 4 × 1 grill type launcher) are installed. The total power up to 450 kW is available for LHCD. An open divertor made by molybdenum on a bottom side and three poloidal limiters made by molybdenum are installed. The poloidal cross sectional view of TRIAM-1M is shown in Fig. 1. The experiments in this paper are executed in limiter discharges.

Almost all of the PFCs in TRIAM-1M are cooled by water to obtain the steady state operation. The difference of the temperature of the water at the inlet and at the outlet of the each water channel was measured with thermistors and the flux of the water in each water channel was also monitored. The heat load has to be calculated from the following equation:

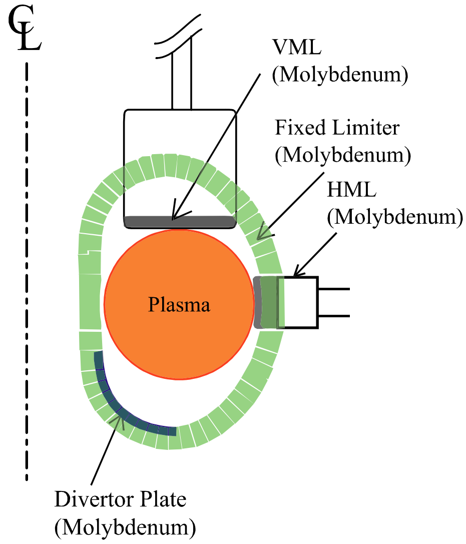


Fig. 1. Poloidal configuration of PFCs on TRIAM-1M. A vertical movable limiter (VML) is installed on the top side of vacuum vessel at a toroidal section and a horizontal movable limiter (HML) is on the low field side at a toroidal section. A single probe, which is fixed behind the limiter surface by 1 mm, is installed on the HML . A divertor plate made of molybdenum is installed on the bottom side of the vacuum vessel in the whole of toroidal section.

$$W\ [J] = 69.8 \int \Delta T_W\ [K] \cdot F_W[\ell/\min]\mathrm{d}t, \qquad (1)$$

where $W$ is the total energy deposited on the plasma facing components during the discharge, $\Delta T_W$ is the increment of water temperature and $F_W$ is the flow rate of cooling water. The time integration should be done until $\Delta T_W = 0$. The total energy, $W$ includes the thermal input at the Ohmic heating (OH) phase and that at full LHCD phase. If the duration of the LHCD phase is significantly longer than that of the OH phase, the value of $W$ is regarded as the energy input during the LHCD phase approximately. The value of $W$ divided by the plasma duration gives the averaged heat load on the PFCs.

The water temperatures were measured with thermistors with the accuracy comparable to 0.01°. To keep the applied voltage to the thermistors constant, 16 batteries of 9 V were used. AD converters of 24 bit sampled every 1 s and the obtained digital data were stored on the memories.

## 3. Experimental results

The estimated heat loads to the fixed limiters and the vacuum vessel including the divertor plates are plotted as the function of the net injected lower hybrid wave (LHW) power, $P_{LH}$ in various full non-inductive LHCD discharges as shown in Fig. 2. In the range of $P_{LH} = 0.005$–$0.09$ MW, the heat loads to the limiter and the vacuum vessel are proportional to $P_{LH}$. When $P_{LH}$ is beyond 0.1 MW, the heat load on the limiter is not fitted so well any more and the dependence on $P_{LH}$ moderates as the heat load on the vacuum vessel is enhanced. The main plasmas in the region of $P_{LH} > 0.09$ MW are drastically changed with a transition phenomena to an enhanced current drive (ECD) mode [6,7]. The plasma current, $I_P$, and $n_e$, were increasing with steady injection of $P_{LH}$. This indicates that the spontaneous transition of the plasma took place. The improvement of the energy confinement and the current drive efficiency, $\eta_{CD}$, occurs in the ECD mode. The different heat load distribution appears in the ECD mode.

There are two processes [5] causing the heat load on the limiters: (1) particle and heat fluxes diffusing from the core plasma to the last closed flux surface (LCFS) and (2) energetic electron heat fluxes via direct losses. The effect of radiation and charge exchange (CX) on the heat load on the limiters was neglected since the surface area of limiters was less than 2% of the total surface area of all PFCs. The heat load via the diffusing process may be estimated by the measurement of the scrape-off layer

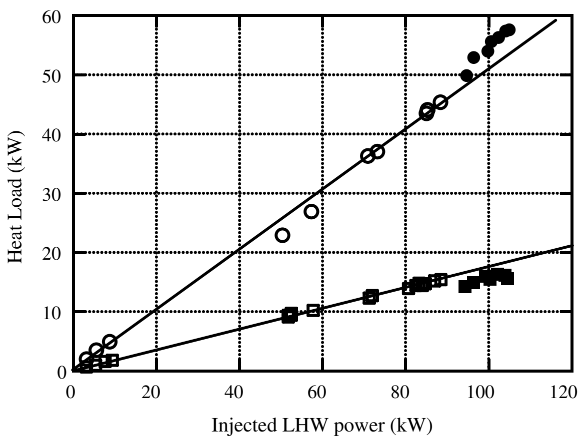


Fig. 2. The dependence of the heat load to the limiters (rectangles) and the vacuum vessel including divertor plate (circles) on the net injected RF power, $P_{LH}$, which is derived form the injected power – the reflected power – the deposited power on the LHW launcher. In the range of $P_{LH} < 20$ kW, the plasmas were sustained by 2.45 GHz LHCD and the other are obtained by the plasmas sustained by 8.2 GHz LHCD. Open characters show the case of the non ECD modes and closed ones show the case of the ECD mode.

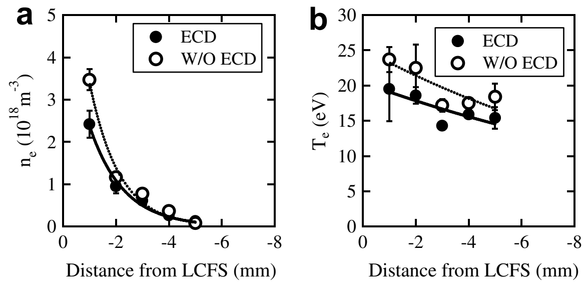


Fig. 3. The profile of (a) $n_e$ and (b) $T_e$ in the SOL region measured by the probe installed on the HML. The values of electron density and ion temperature at the plasma center are $1.0 \times 10^{19}$ m$^{-3}$, 400 eV in the non-ECD mode and $1.5 \times 10^{19}$ m$^{-3}$, 600 eV in the ECD mode, respectively.

(SOL) plasma parameters, such as the electron temperature, $T_e$, and density, $n_e$ [8]. The plasma parameters were measured with a single probe installed on the HML. The profiles of $T_e$ and $n_e$ in the SOL region for a certain discharge are shown in Fig. 3. The values of plasma parameters in the ECD mode are lower than those in the non-ECD mode, although the core plasma parameters in the ECD mode are better. This shows that the energy and the particle confinement are significantly higher in the ECD mode and consequently the heat load on the limiter via the diffusing process is reduced. The measured heat load on the HML was agreed with the heat load estimated form the plasma parameters, which are $n_e$ and $T_e$ in the SOL region as shown in Fig. 3 [9].

Density dependence on heat load on the limiter was measured as shown in Fig. 4. The total heat load on the limiter was proportional to $n_e^{1.5}$ in the range of $n_e = 0.2$–$1.5 \times 10^{19}$ m$^{-3}$. In the range of $P_{LH} > 0.09$ MW, the plasma transition to the ECD mode was observed and the density dependence moderated. This indicates that the heat flux to SOL region was reduced due to the transition to high confinement plasma such as ECD mode.

The increasing of the heat load on the vacuum vessel will be analyzed in this part. The heat load to the vacuum vessel in full LHCD discharges is mainly caused by (1) radiation emitted from the plasma, (2) energetic neutral particles produced by the charge exchange (CX) process, (3) direct loss of energetic electrons, and (4) uncoupled RF power. The heat load due to the uncoupled RF power may be neglected as it is significantly smaller than the heat loads due to the other processes [4,5]. The neutral particle flux in the ECD mode measured with neutral particle energy analyzer is lower than that

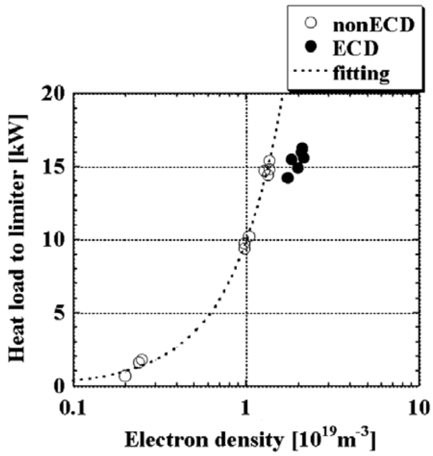


Fig. 4. The $n_e$ dependence of the heat load to the limiters is plotted. Open circles show the case of the non ECD and closed ones show the case of the ECD mode.

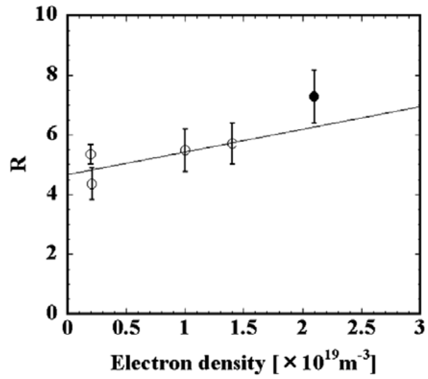


Fig. 5. Ratio, $R$, of the heat load to the vacuum vessel to that to the divertor plate are plotted as the function of electron density, $n_e$. The value of $R = 4.6$ represents the symmetric heat load, because the surface areas and the emissivities of the divertor plates are different from those of the vacuum vessel. Open circles show the case of the non ECD and closed ones show the case of the ECD mode.

in non-ECD mode. Moreover $H_\alpha$ intensities in various poloidal and toroidal positions, which are proportional to the density of hydrogen atoms, are reduced in the ECD mode and this indicates that the CX flux in the ECD mode is also reduced [5]. Unfortunately the radiation power was not measured in any discharges and therefore the variation of the radiation power in the ECD mode is not estimated here. In the ECD mode, the hot spot appeared at the top of the vacuum vessel and consequently the strong damages to the vacuum vessel were observed. This local heat load was caused by the direct loss of the energetic electrons, especially toroidal ripple loss, because the direction of the toroidal ripple loss for the electrons is up in the experimental configuration. As it is difficult to change the direction of toroidal magnetic field in TRIAM-1M, the experiments with the downward electron ripple loss are not executed. This local heat load should lead to the up–down asymmetry of the heat load distribution. This asymmetry was measured by the heat load on the vacuum vessel and the divertor plates, which were installed on the bottom side of the vacuum vessel as shown in Fig. 1. When the heat load due to the radiation and the CX process is dominant, the heat loads on the vacuum vessel and the divertor plates are proportional to their surface area facing the plasma. It should be noted that all of discharges in this paper are in the limiter configuration and the heat load via diffusing process did not affect the heat load on the divertor plates. The ratio, $R$, of the heat load on the vacuum vessel to that on the limiters as the function of $n_e$ is shown in Fig. 5. The ratio of the heat load is increasing with $n_e$, which indicates that the up–down asymmetry clearly appears in high density region such as the ECD mode. This up–down asymmetry may be caused by the direct loss of energetic electrons.

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