SURFACE TEMPERATURE DEPENDENCE OF HYDROGEN BALMAR AND MOLYBDENUM NEUTRAL LINES FROM THE Mo LIMITER IN TRIAM-1M


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Abstract

The limiter surface temperature dependence on hydrogen recycling and molybdenum impurity production behavior was studied with optical spectroscopy during long pulse plasma discharges in TRIAM-1M. It has been observed that the Hα intensity critically depends on the limiter surface temperature. The Mo-I intensity from the hot spot has shown a negative temperature dependence. This is believed to be due to the reduction of heat load and enhanced CX flux due to ion temperature rise.

Keywords-plasma facing component, surface temperature, particle recycling; sputtering and evaporation of impurities, steady state

I. Introduction

Steady state operation (SSO) of the high performance plasma is indispensable for the realization of a fusion power plant. As a consequence of plasma-wall interaction PWI in SSO, it becomes a problem to keep the fuelled particle constant and to reduce impurity influx.

1) A particle controlling problem is mainly caused by re-emission of particles absorbed into plasma facing components PFCs. It has been known that the release of the hydrogen atoms from the metal surface depends on exothermic or endothermic properties of the metal. For tungsten W, endothermic one, the Balmar line intensity from the W limiter shows no temperature dependence but for exothermic tantalum Ta a clear temperature dependence is observed in TEXTOR94[1].

2) For impurity flux from PFCs there are two dominant processes. One is a vaporization process, the other is a sputtering process. For example of the vaporization effects, in TRIAM-1M, it has been observed that an enhancement of metal influxes (Fe, Cr, and Ni) finally terminated the high performance state [2]. It has been reported that the temporal evolution of observed enhanced impurity influxes can be qualitatively well described by an calculated evaporated fluxes from the temperature rise of localized hot spot formed on the PFCs[3].

Thus, PWIs problems, especially particle control and impurity production are very sensitive to PFCs temperature. So it is crucial to investigate how PFCs temperature influences such problems. In this paper, the dependence of the limiter surface temperature T_s on Hα and metal impurity (molybdenum) production will be presented.

II. Experimental apparatus

TRIAM-1M(R0=0.8 m, a × b=0.12 m × 0.18 m) is a superconducting high field tokamak aiming at steady state tokamak operation. The in-vessel PFCs are all metals. In order to study PWI, especially, recycling process and impurity production from a localized interaction region, that is, a hot spot, plasma operation has been performed in the limiter configuration and the following diagnostics are used to observe the hot spot (Fig.1). There are two types of hot spot. One is due to direct interaction by edge plasma, and other is due to energetic electron loss outside the last closed flux surface. The former corresponds to them on fixed poloidal limiters PL, and latter on the movable limiter ML. Both are

Fig.1 The diagnostics arrangement (CCD and IR cameras, IR and visible spectrometers) around the movable limiter.
made of molybdenum. Intensities of Hα and Mo-I from plasma near the movable limiter were measured with a visible spectrometer. The limiter temperature was studied both with a near-infrared spectrometer in the wavelength range from 0.9 µm to 1.6 µm and an infrared camera between 3 µm and 3.25 µm. The latter has been calibrated until ~2000 K with the electric furnace. For visual inspection about the interaction region, a CCD camera was also used. Beside them, the direct interaction between the plasma and PFCs is studied with a calorimeter [4] from viewpoints of the heat deposition and an Hα array around the torus from a viewpoint of a global structure of recycling [5]. Although the deposited heat could be evaluated, the Ts was not directly measured. Using a thermocouple mounted 2 cm away from the surface of the poloidal limiter and a numerical calculation code based on finite element volume method [6] taking into account of the real geometry, the Ts could be deduced. Thus the Hα intensity along the outer chord near the outside limiter is studied as a function of the deduced Ts.

Experimental conditions are follows; Bt=6-7 T, Prf~15 kW for 2.45 GHz and ~100 kW for 8.2 GHz, Ip~15-40 kA, ne~0.1-1x10¹⁹ m⁻³. The discharge duration ranges from 70 s to 132 s. In this case the plasma contact both ML and PLs, and Hα intensities along the verti

cal chord near the outer horizontal part of the PLs are also recorded as the function of the calculated Ts of the horizontal part, as shown in Fig. 3(b). The results also show the existence of Tcrit, although Tcrit is higher than that in case (a). From these data taken in the wide range of the power and density and from different Mo PFCs, it is considered that there exists Tcrit for hydrogen release from Mo PFCs in the long duration discharge.

In TEXTOR endothermic W, whose property is the same as Mo, was used as a limiter material [1]. It has been reported that no increment in the Dβ intensity is observed until 1300 K of the surface temperature. Similar results are also reported in the laboratory experiments [7], in which the surface temperature of W exposed to the plasma is raised ~1000 K. Present results are different from above two results in TEXTOR and laboratory experiments.

### III. Experimental Results

#### 1) Limiter temperature dependence of Hα

In case (a), the limiter configuration is determined by the ML and Hα intensity along the chord viewing the ML is recorded as a function of the Ts of the ML, as shown in Fig. 3(a). Although the injected power was ~15 kW, the surface was heated up to 1200 K, which is high enough for the release of the desorbed hydrogen. Typical two results are shown for #83812 and #84408. The results indicate the existence of some critical temperature Tcrit, above which Hα starts to increase and below which it is kept constant. For higher density and higher power (~70kW) discharge (#84660), Tcrit is still clearly observed. In case (b) higher power (~ 80 kW), higher ne (1 x 10¹⁹ m⁻³) limiter discharges are studied. The discharge duration ranges from 70 s to 132 s. In this case the plasma contact both ML and PLs, and Hα intensities along the verti

![Fig.2](image1.png)

*Fig.2 The setup of Hα chord and poloidal limiter. The used chord is 39.4mm from the outer limiter. The surface temperature of the outer horizontal part of the PL is deduced by thermo couple temperature and numerical calculation.*

![Fig.3](image2.png)

*Fig.3 The surface temperature dependence on Hα emission from (a) the movable limiter and (b) the poloidal limiter*

#### 2) Analysis of Ts and surface state of the limiter

The surface temperature and the surface state were investigated with the IR spectrometer by fitting the obtained spectrum with an assumption of Planck’s blackbody radiation equation,

$$L_{BB} = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1},$$

where $L_{BB}$ is the blackbody radiation, $c$ is the speed of light, $h$ is Planck’s constant, $k$ is the Boltzmann constant, $T$ is the temperature, and $\lambda$ is the wavelength.
where \( h \) is the Planck constant, \( c_0 \) the velocity of light, \( k \) the Boltzmann coefficient, \( \lambda \) the wavelength. The observed spectrum indicates the much higher temperature \( T_s \) than the \( T_{\text{bulk}} \) determined with the IR camera, although the absolute intensity is much lower than the black body intensity of \( T_s \).

We adopted the analysis method reported in TS [8]. The observed spectrum is considered to be the combination of the low temperature component \( T_{\text{bulk}} \) from the main part and high temperature component \( T_{\text{hot}} \) from the very small part,

\[
L(T_e) \sim (1 - \epsilon)L_{BB}(T_{\text{bulk}}) + \epsilon L_{BB}(T_{\text{hot}}) .
\]

Here \( \epsilon \) is the adjustable parameter to fit the intensity, which indicates to a fraction of the hotter emitter. The second term in TS is ascribed to the dust, whose size is around a few \( \mu \)m, deposited on the PFCs.

The analyzed example of the spectrum from the ML in low power discharge in the ML configuration is shown in Fig. 4. The temporal evolution of the dust fraction \( \epsilon \), both dust and bulk temperatures \( T_{\text{hot}} \) and \( T_{\text{bulk}} \) and Mo-I intensity are shown. It is noted that there exists a clear correlation between the growing \( \epsilon \) and the gradually increased Mo-I accompanying bursts. Since the Mo evaporation flux \( \Gamma_{\text{evap}} \) strongly depends on the temperature, the \( T_{\text{bulk}} \) ranging below 1000 K does not contribute to the Mo-I emission. The dust effects are considered.

![Fig. 4 temporal evolution of the dust fraction(a), dust temperature(b), bulk temperature(c), and Mo-I intensity(d) from the movable limiter.](image)

3). Dynamics of hot spot and effects on Mo-I emission

We applied this method to investigate dynamics of hot spot and its temperature effect on Mo-I emission. Although the plasma is operated in the PL configuration and the ML is located at 30-50 mm outside the last closed flux surface, the hot spot is formed on the ML in the high performance ECD (Enhanced Current Drive) mode at high power. It is considered that the hot spot is caused by localized heat load of ripple trapped energetic electron loss [2]. Enhanced metal impurity emission is one of obstacles for maintaining the ECD mode both from viewpoints of the radiation loss and the inverse \( Z_{\text{eff}} \) dependence of \( \eta_{\text{CD}} \).

In order to extend the duration of the ECD mode, the current profile modification have been conducted by combination of two different phases of LHW at 8.2 GHz [9]. During series of this experiment, power modulation at 1Hz was performed near the threshold power for the ECD mode and dynamics of ECD and impurity emission were investigated (Fig. 5). When the power was increased, \( I_p \) was raised but no improvement in \( \eta_{\text{CD}} \) was observed. The ECD transition occurred at 7.7 s and 10.8 s under the constant power phase. \( I_p \) was further increased, and then \( \eta_{\text{CD}} \) was improved. It was also observed that Mo-I intensity was enhanced after the ECD transition was triggered.

![Fig. 5 temporal evolution of the RF power(a), plasma current(b), Mo-I intensity(c), and hot spot temperature(d) in the power modulation experiment](image)

However, the hot spot temperature \( T_{\text{hot}} \) was decreased by 13-15 % from the L-mode phase. Here \( T_{\text{hot}} \) is derived from the method in the previous section and \( T_{\text{bulk}} \) from the IR camera was below 600 K.

Figure 6 shows visible CCD images of hot spot (high brightness point) during the modulation phase. It is clear that during the L mode phase the size and brightness are much larger than those in ECD mode.

![Fig. 6 Evolution of the size and brightness of the hot spot during L mode(7.5s) and ECD mode(8.08s, 8.18s)](image)

The evolution of \( T_{\text{hot}} \) is consistent with those of the size and brightness of the hot spot. This result supports that during the ECD mode energetic electron loss is actually reduced to lead the reduced heat load on the ML. This is also supported by the fact that hard X-ray intensity is increased and the Abel
inverted profile changes to a more peaked one during the ECD.

Thus, the negative dependence of Mo-I on T_{hot} is not simply explained by the evaporation flux both from the hot spot and the bulk surface. The improved energy confinement during the ECD leads to ion temperature \(T_{\text{ion}}\) of \(~0.8\) keV and the internal transport barrier is formed in the core region for ion temperature profile [10]. Since there is no energy input path directly from RF to ions, \(T_{\text{ion}}\) is not increased during the L-mode, but is increased by ECD transition. This is clearly shown in Fig. 7(a). Temporal evolution of the charge exchange CX flux at the energy of \(~1\) keV is plotted in the same discharge in Figs. 5 and 6. Since the energetic CX flux dominates the Mo sputtering process, the relation between the Mo-I intensity and the CX flux is studied in Fig. 7(b). Although both signals show a positive correlation suggesting the enhanced Mo-I by sputtering, the saturation tendency of Mo-I as a function of CX flux cannot be explained only by the sputtering process.

\[
\Gamma_{\text{total}}(t) = a\Gamma_{\text{eva}}(t) + b\Gamma_{\text{spu}}(t),
\]

where \(a\) and \(b\) are adjustable constant parameters. Comparison is presented in Fig. 8. The observed Mo-I intensity is nicely reproduced by this modeling. Thus it is concluded that the temporal evolution Mo influx during the ECD is caused by both reduced evaporation process from the shrank hot spot and enhanced sputtered process by CX flux.

IV. Discussion and Summary

The surface temperature dependence on the H_{\alpha} and Mo-I intensities has been investigated from viewpoints of particle recycling and impurity production.

It is found that there exists the critical temperature above which the H_{\alpha} intensity is increased as Ts increases. In order to understand this aspect of the endothermic Mo, the vacuum deposition of Mo on SUS plate and D beam injection experiments have been done. By the thermal desorption spectroscopy it is found that there exists a strong D trapping cite when the thickness of thin layer is about the projected range of D ions [11]. The observed variation in T_{crit} is left for future.

The metal impurity influx is also investigated taking into account of both evaporation and sputtering processes. Even if the PWI region is localized on PFCs, it can influence the discharge duration when the handling power becomes increased. The time variation of Mo influx in power modulation experiments can be well explained by reduced evaporation and enhanced sputtering processes. These processes are a consequence of the transition of plasma confinement properties.

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