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Surface temperature effects on hydrogen and impurity release from the limiter studied by means of visible and near infrared spectroscopic measurement in TRIAM-1M

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Abstract

Tokamak operation has been performed under the localized plasma wall interaction conditions in TRIAM-1M, using a water cooled rail movable limiter (ML) made of Molybdenum. The limiter surface temperature dependence on hydrogen recycling and neutral molybdenum impurity production behaviour has been studied using visible as well as infrared spectroscopy during low power long pulse and high power short pulse discharges. In these experiments it is considered that escaped energetic electrons are lost mainly on ML and localised heat deposition makes a 'hot spot' on ML. It has been observed that H_2, H_α and MoI intensities critically depend on the hot spot temperature (T_{hot}) and enhanced recycling due to localized PWI on ML can fuel the discharge without any external fueling source.

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1. Introduction

The understanding of the retention and release processes of H_2 from the plasma facing component

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(PFC) is essential to plasma density control in steady state operation of fusion reactors. In addition to the density control, impurity influx from the PFCs is also required to be controlled from a view point of dilution. The density controlling problem is caused mainly by recycling of the fuel particles. It has been known that the release of H_2 from the metal surface depends on exothermic or endothermic properties of the metal. For tungsten (W), endothermic one, Balmer line intensity shows no temperature dependence but for exothermic tantalum (Ta) clear temperature dependence was observed in TEXTOR-94 [1].

For the production of the impurity influx from PFCs two dominant mechanisms are known. One is evaporation and the other one is sputtering [2]. It has been reported that the temporal evolution of observed enhanced impurity influxes can be qualitatively well described by a calculated evaporated flux from the temperature rise due to local hot spot on PFCs [3].

Thus the hot spot temperature (T_{hot}) of PFCs plays an important role to release both H_2 and impurity atoms through different physical processes. In this paper, using spectroscopic measurements (200–1600 nm) looking at the movable Mo limiter on which the heat is locally deposited, dependencies of T_{hot} on release of H and Mo are studied [4]. The emissions from H_2 and H are used to evaluate the temperature dependent physical process for H release from the Mo surface. The emission in the near IR range is used to evaluate T_{hot} and to deduce the fraction of the highest bright area on the ML surface.

2. Experimental apparatus and conditions

2.1. Experimental set up

TRIAM-1M ($R_0 = 0.8$ m, $a \times b = 0.12$ m $\times$ 0.18 m) is a high field superconducting Tokamak aiming at steady state Tokamak operation [5]. The in-vessel PFCs are all metals. In order to investigate the PWI effects on tokamak operation a water cooled rail movable limiter (ML) was inserted vertically into the plasma and thus PWI could be localized on the movable limiter (Fig. 1). The toroidal width of the ML is 30 mm and the radial length is 160 mm. The diagnostics tools used for investigating the PWI on ML surface are also shown in Fig. 1.

It has been pointed out that the line intensity ratio of Balmer series is sensitive to the atomic

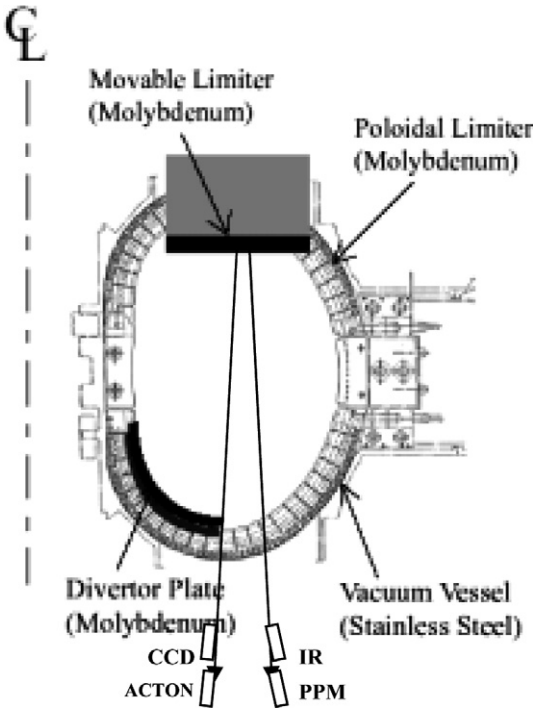

Fig. 1. Cross-sectional view of main chamber at the section of ML. CCD camera and other optical measurement tools are shown schematically.

and molecular fraction and the electron density [6]. The Balmer ratios, H_α/H_β and H_γ/H_β, are measured simultaneously with a plasma process monitor (PPM) which covers from 200 nm to 900 nm and measures MoI lines also (386 nm). The Fulcher line ((0–0)Q1: 601.8 nm) from H_2 is measured with another spectrometer (ACTON) equipped with a CCD (ANDOR: 2048×512). These data are used to evaluate the hydrogenic and molecular flux from the limiter. The hot spot temperature on the limiter is determined from the IR spectrum from 900 nm to 1600 nm with an assumption of the blackbody emission. Comparing the absolute blackbody intensity from the determined T_{hot} with the measured intensity the fraction of the 'hot area' is also deduced [5]. It should be noted here that the visible spectrometer is equipped with a lens ($\phi = 30$ mm) to collect only parallel light, but PPM and IR can see the whole ML surface (160×30 mm^2). For visual inspection of the interaction region a CCD camera was also used.

The main metal impurity ions are Mo and the radiation is measured by VUV (MoXIII 34.7 nm) spectrometer.

2.2. Experimental conditions

The experimental conditions are as follows:

$B_t = 6$–7 T, $P_{rf} = 10$–20 kW for 2.45 GHz and 40–300 kW for 8.2 GHz (along with ECH power), $N_e = 0.1$–4.0×10^{19} m^{-3}. The discharge duration ranges from several seconds (3–20 s for high power case) to several minutes (~20 min for low power case). To study the hot spot temperature effect on recycling from localised PWI the limiter configuration is varied by inserting the movable limiter so that LCFS is defined by ML. Lower hybrid waves are used to sustain the full current drive plasma for such types of discharges. In order to form a hot spot loss of counter moving energetic electrons are enhanced by adding backward lower hybrid waves. These electrons are lost mainly on ML and localized heat deposition makes a hot spot on ML. Fig. 2 shows typical evolutions of total rf power, T_{hot}, N_e, and feedback controlled gas puff voltage for such type of discharges. Localised PWI on ML dominates the global recycling and enhanced particle fueling from the ML with the sharp rise in T_{hot} gives rise to increase in electron density without gas puffing.

In present experimental condition, since the increase in surface temperature is due to the formation of the 'hot spot' on ML, temperature is not uniform on the whole ML surface. Also, it has been confirmed that ANDOR viewing area is ~2 cm away from the hot spot location.

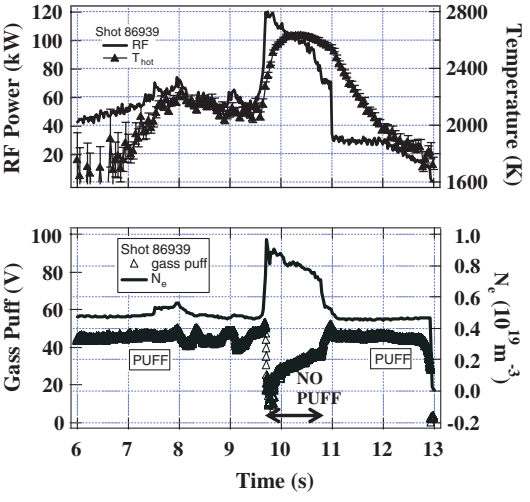

Fig. 2. Time evolutions of total rf power, T_{hot}, gas puff voltage and electron density for typical discharges. Feedback controlled puff voltage is reduced with the sharp increase in electron density. Increase in RF power indicates improved coupling.

3. Experimental results

3.1. T_{hot} dependence of H_α emission

In Fig. 3 time evolutions of H_2, H_α intensities and T_{hot} for a typical discharge are shown. It should be noted here that T_{hot} is measured by infrared spectrometer and the temperature is deduced by fitting the observed spectrum with an assumption of blackbody emission [4,5,7]. Since the observed spectrum is very much sensitive to the formation of 'hot spot' on the ML surface IR spectrometer gives the temperature of the hot spot. The bulk temperature of the ML surface is found to be much less compared to the hot spot temperature [4,5]. It is clear from Fig. 3 that there exists a critical temperature beyond which H_α intensity increases rapidly and below which it is kept almost constant. Similar trend is observed in other Balmer line intensities also. In TEXTOR endothermic W, whose property is same as Mo, was used as limiter material [1] and no increment in the D_β intensity was observed until 1300 K of the surface temperature. Similar results (for <700 K) are also reported in the laboratory experiments [8]. In the present experiment, however, T_{hot} is varied on a wide range and existence of a critical temperature is observed.

3.2. T_{hot} dependence of molecular hydrogen (H_2) emission

From the time evolution of Fulcher line (($v = 0$–0)Q1) intensity, as shown in Fig. 3, it is found that initially H_2 intensity remains almost constant, even if T_{hot} rises. But a sharp rise is observed when T_{hot}

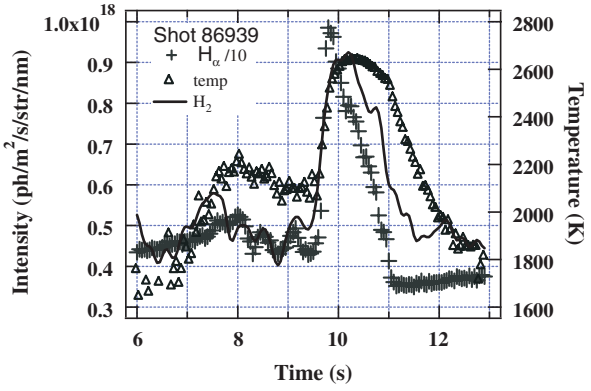

Fig. 3. Evolution of H_2 and H_α intensity and T_{hot} on the ML surface.

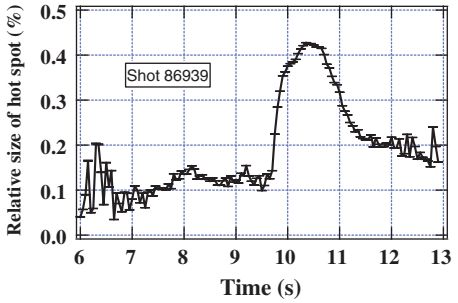

Fig. 4. Evolution of hot spot fraction on ML surface.

increases beyond 2200 K (~9.5 s). The relative size of the hot area is also found to increase sharply at this time (Fig. 4). Finally, H_2 intensity, T_{hot} and relative size of the hot area start decreasing after ~10.2 s. It has been reported in D^+ irradiation study [9] on resistively heated bulk Mo sample that molecular reemission dominates below 1200 K and atomic reemission dominates beyond this temperature. In present experimental situation ML is heated by localized plasma wall interaction and H_2 emission is considered to occur from the co-deposited layers on the ML surface which can be formed due to repetitive discharges and subsequent heating and cooling of the ML surface. The observed H_2 intensity behaviour is discussed in Section 4.1. From the observed Balmer line intensities by PPM, the line ratios have been calculated and are shown in Fig. 5. It is seen that the line ratios remain almost constant up to 9.5 s. At $t = 9.5$ s, a sharp rise in T_{hot} gives rise to increase in Balmer and Fulcher line intensities. A sharp change is also observed in the line ratios and following the results discussed in [6], change in molecular to atomic fraction is found out. A factor of almost three rise is found in the molecular fraction. A factor of two rise in H_2 intensity is directly observed by ACTON spectrometer. N_e also is found to increase by a factor of two.

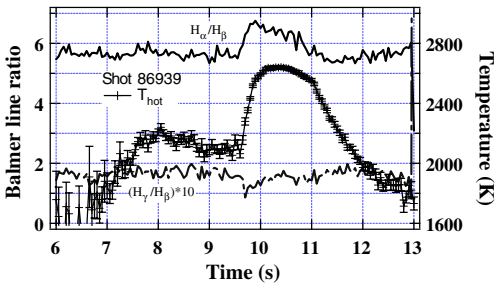

Fig. 5. Time evolution of Balmer line intensity ratios. Evolution of T_{hot} is also shown.

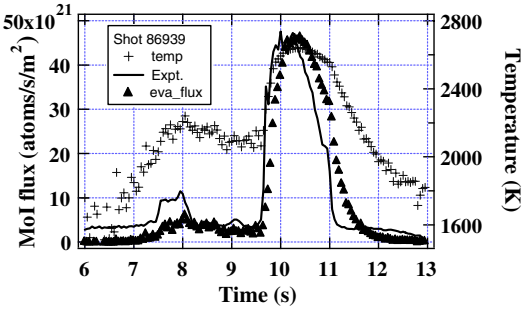

Fig. 6. Evolution of MoI Flux and T_{hot} ($\phi_{hotspot} \sim 1.56$ mm is assumed). Theoretically calculated evaporation flux is also shown.

3.3. T_{hot} dependence of MoI emission

Fig. 6 shows the time evolution of T_{hot} and MoI flux, calculated from observed MoI line intensity. A sharp rise has been observed in the MoI flux when T_{hot} is more than 2200 K. Theoretical calculation of evaporation flux (Γ^{eva}) was done using single atom model [10] and is also shown in the same figure. It is found that experimentally observed MoI flux (Γ_{Mo}) during the sharp rising phase of T_{hot} matches qualitatively well with Γ^{eva} for an assumed hot spot diameter of 1.56 mm. This hot spot size is found to be in good agreement with the SEM observation. Observed MoI flux before 7.5 s is considered to be due to sputtering, since evaporation flux is almost negligible during this time due to lower values of T_{hot}. Similar behaviour of MoI flux has been observed in TEXTOR [11] with limiter surface temperature in NBI condition. Though the enhanced Mo source does not give rise to increase in VUV MoXXXI line in TEXTOR, enhancement in Mo XIII line has been observed in present experiment.

4. Discussion

4.1. Hydrogen recycling behaviour with hot spot temperature

Fig. 7 shows both H_α and H_2 intensity variation with T_{hot}. It is clearly seen that for H_α case, intensity rises sharply after T_{hot} reaches a critical value of 2200 K and reaches a maximum value. Then it starts decreasing even if T_{hot} increases. It seems that with the sharp rise of T_{hot}, enhanced emission of H_α takes place from the co-deposited layers on Mo surface. But once all retained hydrogen comes out, H_α signal starts decreasing.

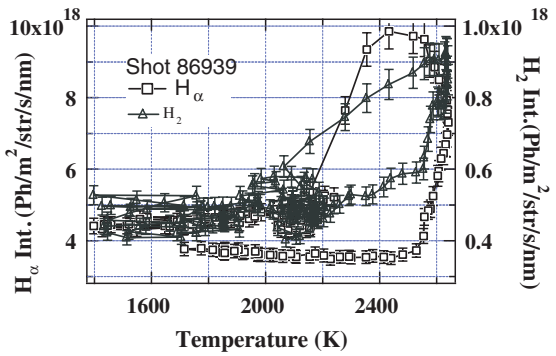

Fig. 7. H_α and H_2 intensity variation with $T_{hot.}$

H_2 intensity variation is found to follow T_{hot} variation. As mentioned earlier, the H_2 observation area is ~2 cm away from the hot spot location. Three dimensional heat flow equation is solved numerically in real ML geometry using cubic finite element method to get the surface temperature variation around the hot spot location with an assumption of the size ($\phi = 10$ mm) on which heat flux is locally deposited. It is found that even if T_{hot} can rise up to 2600 K, temperature can be within 300–400 K at a distance of 2 cm from the hot spot location. In discharges with 2.45 GHz lower hybrid waves, the surface temperature of the ML was within 300–500 K when no hot spot was formed and no sharp rise in H_2 intensity was observed with the variation of surface temperature. But temperature can increase in the immediate nearby areas with the increase in the size of hot spot and thus can give rise to enhanced H_2 emission. Thus H_2 intensity evolution can be explained by considering the increase of both temperature and size of the hot spot. It is thought that both H_2 and H_α are dominantly emitted from the hot spot and it's immediate nearby areas.

4.2. Simultaneous emission of impurity and H_2 from hot spot location

Another interesting result of this experiment is the simultaneous emission of MoI, H_2 and H_α from the hot spot location beyond a critical temperature (Figs. 6 and 7). It is well known that PWI causes erosion of the materials which can be deposited back on to wall surface to form layers containing all elements used as PFCs. Such deposition-dominant layers have been observed in TRIAM-1M [12]. The hydrogen concentration, H/Mo, in thin co-deposited layer has been found to be ~0.1 [13]. The amount of retained hydrogen is found to increase with the thickness of the co-deposited layer as well as with the defective structure of the co-deposits. It is highly probable that such co-deposited layers are formed on the ML surface due to shot history as well as repetitive melting due to hot spot formation and subsequent cooling down of the ML surface. It is considered that a large amount of hydrogen is retained in these co-deposited layers and is emitted when these layers are broken at critical T_{hot}. Formation and breaking of such layers can happen in the same discharge and deposit properties also can vary with plasma conditions. It is considered that the observed enhanced H_2 emission with the sharp rise of hot spot temperature, caused due to local PWI, may be different from the results observed in a standard TDS experiment in laboratory.

5. Conclusion

The T_{hot} dependence on H_α, H_2 and MoI intensities has been investigated from viewpoints of particle recycling and impurity production. A critical T_{hot} is found to exist beyond which $H_\alpha$intensity first increases rapidly with T_{hot} but starts reducing when all the retained hydrogen comes out from the hot spot location. But during rapid rising phase of the intensity, local hot spot can increase the electron density even in the absence of external fueling source. The metal impurity influx is investigated taking into account of evaporation process. Simultaneous emissions of hydrogen as well as impurity influxes are thought to be due to the existence of co-deposited layers on ML surface. These layers can be formed due to shot history and repetitive hot spot formation on ML surface and subsequent cooling. Even if the PWI is localized on the ML surface, it is found to affect the global plasma behaviour.

Acknowledgements

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