

## Steady State Tokamak Operation with Real Time Measurements of Recycling, Heat Load, and Molybdenum Deposition in TRIAM-1M

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### 1. Steady State Tokamak Operation

With the goal of addressing the critical issues of steady-state tokamak operation (SSTO) [1] of future fusion devices, experiments aiming at ‘day long operation at high performance’ have been carried out in a limiter configuration of TRIAM-1M plasma ( $R_0 = 0.84$  m,  $a \sim 0.12$  m and  $B = 6-7$  T). The record value of the discharge duration was updated to 5 h and 16 min (Fig. 1a) by toroidally localizing the particle recycling profile and the heat deposition at a limiter with better heat removal capability and by reducing the surface temperatures of plasma facing components PFCs. They consist of three poloidal limiters PLs, divertor plates, movable limiter ML, vacuum vessel, bellows, and LH antenna. The first three are made from molybdenum,

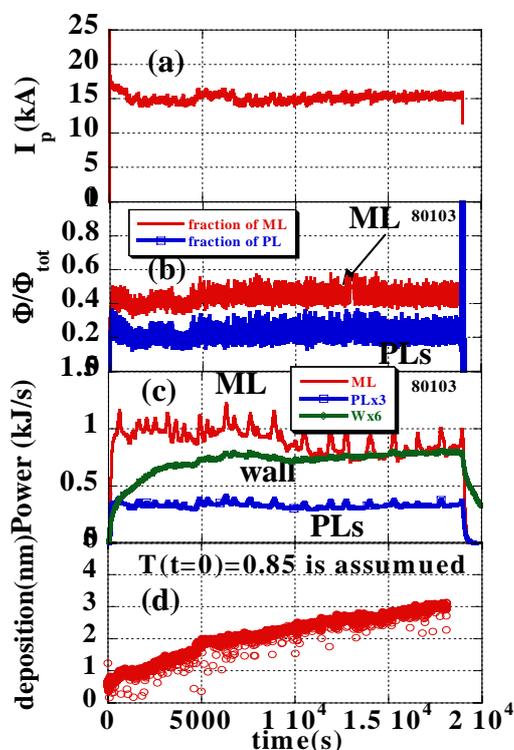


Fig. 1 Five-hour discharge; (a)  $I_p$ , (b) fractions of recycling particles, (c) heat load on PFCs, and (d) Mo deposition thickness.

and others are stainless-steel. Low-Z coating on the PFCs have never been done. So far, visible and VUV spectroscopic observations and material analysis indicate that the surfaces of PFCs are covered by a molybdenum thin layer. Real time measurements of metal deposition on PFCs during a single shot (~5 hours) and ex-situ study of hydrogen co-deposition on a specimen exposed to a single discharge (~72 min) have been progressed in order to understand temporal change in wall pumping rate. In this paper, the following results will be presented; 1) the toroidal distribution of the recycling flux and the contribution of each PFCs to the total

particle flux, 2) the heat deposition profile and the fraction of the heat load deposited on PFCs, and 3) the deposition of Mo thin layer and retained hydrogen. Finally, we will summarize the results.

## 2 Toroidal distribution of the recycling flux and contribution of the ML

An  $H_\alpha$  measurement system consists of fiber optics, narrow  $H_\alpha$  filters and photomultipliers is used to measure toroidal (six positions) and poloidal (seven vertical chords) distributions. A fan array with horizontal twenty five chords is also used to evaluate the hydrogen influx (656 nm), molybdenum influx (386 nm) and oxygen influx (442 nm) with time resolution of  $\sim 0.1$  s [2]. At the same port a spectroscopy covered with a wide wavelength range (200-800 nm) is installed to monitor the history of discharges or the time evolution of the spectra in the visible range during the shot. The feedback control of the hydrogen influx is performed with a spectroscopy fixing at  $H_\alpha$  line. During 5 hour discharge,  $H_\alpha$  intensities for initial 500~1000 s can be fitted by  $\sum A_i \exp(-t/\tau_i)$ , where  $A_i$  and  $\tau_i$  are amplitude and time constants of 5s, 50s and 2000 s, for example. Then they are kept constant by feed back controlled gas puffing. The normalized poloidal profiles are found to be almost the same, although the intensity at the ML is extremely high indicating the localized particle recycling. The toroidal distribution at 18000s is shown in Fig.2. In order to evaluate the fraction of particle source rate we used the following simple relation  $\dot{N} = 2\pi a(\Phi_w 2\pi R + \Phi_{ML} \lambda_{ML} \sqrt{\pi} + 2\Phi_{PL} \lambda_{PL} \sqrt{\pi})$ , where  $\Phi_w, \Phi_{ML}, \Phi_{PL}$ ,  $\lambda_{ML}, \lambda_{PL}$  are flux determined from  $H_\alpha$  intensity and characteristic toroidal length, respectively.

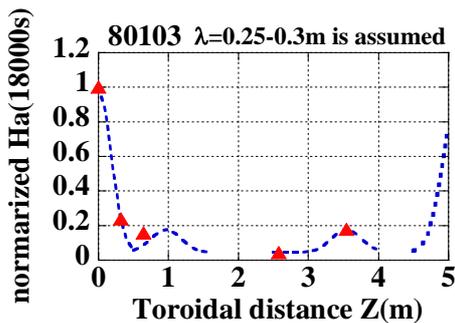


Fig.2 The toroidal distribution of  $H_\alpha$  along the center chords(triangles). Dotted curves are fitted curves.

The spectrum analysis based on the Zeeman effects [3] for the  $H_\alpha$  line shows the fraction of energetic hydrogen atoms with  $\sim 6$  eV is twice that of the low energy atoms of  $\sim 0.4$  eV. The  $\lambda$  is consistent with the Monte Carlo calculations done in Gamma-10 with similar parameters [4]. In Fig. 1b the fraction of each component is shown during the discharge and the ML contributes  $\sim 40\%$  of the total particle recycling source rate.

## 3. Heat load distribution, power accountability and very low frequency oscillations

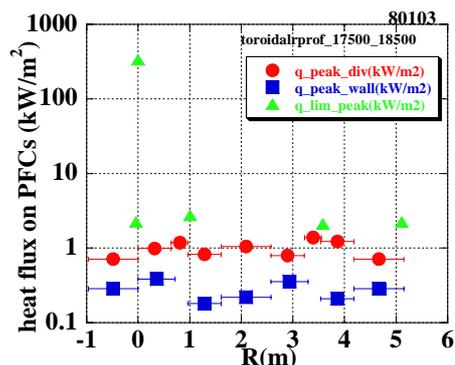


Fig.3 The toroidal distribution of the average heat flux on each PFCs.

A calorimeter system with 32 thermistors for cooling water temperature of PFCs were used to evaluate the distribution of the heat load deposited on the PFCs. Since the ML with high cooling capability is used, the surface temperatures of PFCs could be successfully reduced by  $\sim 100$  K compared with those in discharges with PLs, in which configuration the contact part of PLs to the plasma is not directly cooled. The IR measured surface temperature of ML is much less than 600K.  $T_{\text{wall}}$  and  $T_{\text{limiter}}$  of PLs could be reduced to 330K and 450K, respectively. After 7000 s, the steady state is established for the temperature profiles. A fraction of 34 % of the total heat load is deposited on the ML, which is the same order of the particle recycling fraction. The rest is distributed on PLs (10%), and wall (34%) and divertor plates (22%). The averaged heat flux is evaluated and the toroidal distribution is shown in Fig. 3. The toroidal structure for the wall is under consideration. As shown in Fig. 1(c), the spikes with 20% in amplitude and the frequency of  $\sim 10^{-3}$  Hz are observed on thermal load signals. The horizontal movement towards the outer board side of the  $H_{\alpha}$  profile is also observed at the same frequency. This modulation seems to be caused by the variation in coupling between rf and plasma. It is considered that the plasma termination is related to the spike phase.

#### 4. In situ measurement of Mo deposition thickness and ex situ analysis for a relation between hydrogen retention and Mo thickness

As it has been pointed out in ref. [5] that the wall pumping has a large impact on controlling of plasma density in SSTO. Hirooka et al. had analyzed that the wall pumping is actually necessary from the particle control point of view based on the model calculation of global particle balance [6]. In order to follow the temporal change in metal deposition on PFCs, two kinds of spectroscopic transmittance and reflectance measurements have been done during 5 hour discharge. From the measurement of the transmittance of the plasma light through a viewing window located at 75 mm from the LCFS and the assumption that the Mo atoms were deposited on it, the deposition rate of  $1.1 \times 10^{16}$  Mo/m<sup>2</sup>/s was determined from  $\sim$  three nm thickness (Fig. 1d) and wall pumping rate of  $3.8 \times 10^{15}$  H/m<sup>2</sup>/s was deduced at this position far from the LCFS. Here, the H/Mo of 0.35 is used [7].

Ex situ surface probe analysis has been performed to study a relation between the

metal deposition and hydrogen retention in the SOL region ( $a < r < a+30$  mm) [8]. The data are taken for a single discharge for 72 min with the ML. Using high energy He beam, Rutherford backscattering spectrometry is used to analyze chemical composition and thickness of the deposited layer. The Mo deposition rate on the specimen located at 7 mm behind the PL is estimated  $3.9 \times 10^{17}$  atoms/m<sup>2</sup>s and it is  $0.64 \times 10^{17}$  atoms/m<sup>2</sup>s on the specimen facing main plasma. These values are consistent with the optically determined value taking the radial deposition profile into account. The difference for two specimens is considered to be due to variations in the sticking rate and sputtering rate depending on elementary processes in plasma surface interaction. Based on elastic recoil detection the retained hydrogens on two specimens are estimated to be  $\sim 1.3 \times 10^{16}$  atoms/m<sup>2</sup>s and  $0.64 \times 10^{16}$  atoms/m<sup>2</sup>s, respectively. These values are less than 1 % of the hydrogen influx ( $\sim 3 \times 10^{18}$  H/m<sup>2</sup>s ) determined by spectroscopic measurement and are close to the wall pumping rate of  $\sim 1.5 \times 10^{16}$  atoms/m<sup>2</sup>s determined from the particle balance[5].

## Summary

The SSTO experiments have been carried out from a view point of control of PWI and wall pumping effects by metal impurity. Using ML the global aspects of particle recycling and heat deposition around the torus were successfully controlled. Especially, the maximum surface temperature of the PFCs could be kept below 450 K and it played an important role to better control the density during 5 hours. The fraction of the recycling flux and heat deposition are found to be 30~40 % for the ML. The real time measurement of the Mo deposition thickness on PFCs is demonstrated and a relation between the hydrogen retention and the deposited Mo is investigated for the specimens exposed to a single shot.

## Acknowledgement

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