Steady state plasma operation in the superconducting tokamak
TRIAM-1M and the QUEST project

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Abstract: The steady state tokamak operation has successfully been carried out in the superconducting
tokamak TRIAM-1M. In the steady state operation, hydrogen recycling and the related plasma-wall
interaction phenomena were studied from macroscopic and microscopic points of view. And the QUEST
project is briefly introduced.

Keywords: Steady state operation, Plasma-wall interaction, Hydrogen recycling

1. INTRODUCTION

Steady state operation (SSO) is one of the most critical
issues for the future fusion reactor. As a plasma duration
becomes longer, phenomena with long characteristic time
such as current diffusion and plasma-wall equilibrium
time play more important role for SSO.

In TRIAM-1M, a superconducting coil system and
lower hybrid current drive (LHCD) systems had been
developed and ultra-long duration plasmas were
successfully achieved [1]. Although TRIAM-1M was shut
down, a number of fruitful researches related to SSO had
been carried out. One of those is hydrogen recycling. It is
important from the viewpoint of density control.
Moreover, it relates to tritium inventory, since a wall
plays both roles of a particle sink and a particle source. In
this paper, we focus on the hydrogen recycling during
long duration plasmas and its relating plasma-wall
interaction (PWI). And we briefly introduce the new
spherical tokamak QUEST that is now constructing in
Kyushu University.

2. TRIAM-1M tokamak and steady state operation

Figure 1 shows a bird’s-eye view of TRIAM-1M. Sixteen superconducting toroidal field coils, which are
made of Nb3Sn, are installed. Toroidal magnetic field is
up to 8 T. The plasma vacuum vessel has a D-shaped
cross-section with the horizontal length of 0.26 m and the
vertical length of 0.38 m. The poloidal field coils, which
are made of normal conductor Cu, are mounted on the
vacuum vessel. The major radius of the center of the
vacuum vessel is 0.84 m. The whole machine is installed
inside a bell-shaped vacuum vessel (i.e. a bell-jar) for
thermal insulation. Extension pipes connect between the
plasma vacuum vessel and the bell-jar.

One of the features of TRIAM-1M is that all of the
plasma facing components are made of high Z materials:
the poloidal limiters and the divertor plates are made of molybdenum, and the main chamber is made of stainless
steel. A low Z material coating has never been done. A
movable limiter (ML) of which front edge is made of
molybdenum has been installed at the same section as the
fixed poloidal limiter (PL) and the pumping port. It is
thermally insulated from the main chamber and has good
cooling capability. The ML can approach from above to
the plasma during the discharge by remote control.

The heating and current drive systems in TRIAM-1M
are summarized in table 1. The ultra-long discharge of
which density range is less than about 0.2 x 10^{19} m^{-3}
are sustained by the 2.45 GHz LHCD system. The high
density and long duration discharges are sustained by the
8.2 GHz LHCD systems. It should be noted that steady
state and long duration plasma can be sustained by LHCD
power alone.

Table 1 Parameters of the heating and current
drive systems in TRIAM-1M.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Max. power (kW)</th>
<th>Pulse duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>50</td>
<td>CW</td>
</tr>
<tr>
<td>8.2</td>
<td>200</td>
<td>CW</td>
</tr>
<tr>
<td>8.2</td>
<td>200</td>
<td>CW</td>
</tr>
<tr>
<td>ECH</td>
<td>170</td>
<td>5 sec</td>
</tr>
</tbody>
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Figure 2 shows the progress of the steady state tokamak operation in TRIAM-1M. It can be seen that the plasma duration became longer step by step. In each step, the control system such as plasma position control or fueling control was developed. As far as the fueling control is concerned, the control system using the Hα line intensity was developed [1]. The gas feed was feedback controlled by a piezoelectric valve so as to keep the Hα line intensity at the central chord constant. The Hα line intensity is related with the number of hydrogen atoms that are ionized per unit time, i.e. particle influx to the plasma. Thus the particle influx to the plasma was controlled during the discharge.

3. Experimental results

3.1. Particle balance model in the vacuum vessel

A particle balance equation in the vacuum vessel is written by the following equation [2]:

$$\frac{dN_H^0}{dt} + \frac{dN_H^p}{dt} = \Gamma_{\text{fuel}} - \Gamma_{\text{pump}} - \Gamma_{\text{wall}},$$

where \(N_H^0\) is the total number of hydrogen neutral atoms in the main chamber, \(N_H^p\) the total number of hydrogen ions in the plasma, \(\Gamma_{\text{fuel}}\) the fueling rate, \(\Gamma_{\text{pump}}\) the pumping rate of the external pump-unit and \(\Gamma_{\text{wall}}\) the net wall pumping rate. A schematic diagram illustrating the particle balance flow is shown in Fig.3. The net wall pumping rate means the balance between the hydrogen absorption rate \(\Gamma_{ab}\) and hydrogen release rate \(\Gamma_{rv}\).

3.2. Impact of the wall temperature on hydrogen recycling

Figure 4 (a) shows the time evolution of the wall inventory in the ultra-long discharge in TRIAM-1M. The horizontal axis indicates the plasma duration. In the first 30 min, the wall pumped the hydrogen, i.e. it played a role of the particle sink. The averaged wall pumping rate is evaluated to be 2.4 x 10^16 atoms m^-2 s^-1 from the equation (1). At t~30 min, the role of the wall changed to the particle source. After that, the wall released the hydrogen until the end of the discharge. During the discharge, the wall temperature increased due to the heat load from the plasma as shown in Fig.4 (b). The wall temperatures were measured on the side of the main chamber opposite the plasma by thermocouples. The temperature rise depends on the distance of the measuring point of the thermocouple from the cooling channel on the main chamber. The wall temperature increased partly up to 120 °C and it was measured near a bellows part that was used to increase the one-turn resistance of the main chamber in the toroidal direction and was not cooled. It is considered that the temperature rise in the wall is attributed to the transition of the wall role from the particle sink to the source.

On the other hand, when the increase in the wall...
3.3. Impact of co-deposition on hydrogen recycling

Material probe experiments were carried out in the low density (~1 x 10^{18} m^{-3}) and high density (~1 x 10^{19} m^{-3}) long duration discharges [4-6]. The probe head with various kinds of specimens were inserted in the scrape-off layer (SOL) and exposed to long duration plasma, and then the following analyses were carried out. The chemical composition and thickness of a deposited layer were estimated using Rutherford backscattering spectrometry (RBS) and the concentration of hydrogen retained in the deposited layer was estimated using the elastic recoil detection (ERD). The microstructure of the deposits was observed by means of transmission electron microscopy (TEM). The major element of deposits is molybdenum. The grain size of the deposits is 1-2 nm or 10-20 nm and it depends of a setting position of the specimen and plasma condition. The wall pumping rate, \( \Gamma_{wall} \), which is estimated from the total amount of hydrogen retention in the co-deposits on the specimen and the discharge duration, seems to be consistent with the wall pumping rate estimated from the global particle balance \( \Gamma_{GPB} \) using the equation (1). \( \Gamma_{wall} \) means so-called static retention, since it is estimated after the plasma discharge. On the other hand, \( \Gamma_{GPB} \) means dynamic retention. Co-deposition of hydrogen with molybdenum is recognized as possible candidate for the continuous wall pumping in the long duration discharge.

3.4. In situ measurement of thickness of co-deposited layer

An in situ and real time measurement system of erosion and deposition has been developed, which is based on interference of light on a thin semi-transparent layer of re-deposited material on substrate [7]. A sapphire window of 4mm thickness is used as a substrate, which is also used for Thomson scattering measurement. It is located at about 75 mm away from the last closed flux surface of the plasma which lies at the center of PL. A fiber optic bundle which is composed of 450 optic fibers with the diameter of 100 µm is attached to the air side of the window. The optic fibers are mixed statistically. The fiber optic bundle is pushed on the window surface by spring action to avoid a gap between them due to vibration during the plasma production. Half of the optic fibers is used to illuminate the substrate with laser light (\( \lambda \approx 635 \) nm) and the other half guides the reflected light back to a photodiode. In order to avoid plasma light, an interference filter is mounted in front of the photodiode. The intensity of the laser light is monitored by the other photodiode. Figure 6 shows time evolution of the wall inventory and growth of the deposited layer in the 5-hour discharge that is shown in Fig.5 (a) [8]. The averaged growth rate of the deposited layer is \(-2.3 \times 10^{-4} \) nm s\(^{-1}\), i.e. \(-1.5 \times 10^{-6} \) Mo m\(^{-2}\) s\(^{-1}\). The wall inventory, which is obtained from temporal integration of the wall pumping rate, reaches \(-8 \times 10^{17} \) H. It is found that the both of wall inventory and growth of the deposited layer indicate similar tendency. Although the spatial deposition profile on the plasma facing component is necessary for quantitative analysis, monotonic increase of the deposited layer suggests that the continuous wall pumping is attributed to the co-deposition of hydrogen with eroded Mo atoms.

4. QUEST project

The specified purposes of QUEST project are as follows:

1. To examine the steady state current drive and plasma generation of the spherical tokamak as academic basics research on a high beta and steady state.
2. To comprehensively establish recycling control based on wall temperature control, advanced wall control under high plasma performance, as academic basics research on steady state operation.
3. To improve diverter concepts by taking full advantage of a magnetic configuration specific to the spherical tokamak and to establish the way of controlling particles and thermal loads during long duration operation.
4. To conduct basic research for comprehensively understanding toroidal plasma physics.

The nominal parameters of QUEST are as follows: a major radius \( R=0.68 \) m, a minor radius \( a=0.4 \) m, aspect ratio \( R/a=1.7 \), toroidal magnetic field \( B=0.25T \) (steady state). The first plasma is expected to be produced in 2008.

5. Summary

In TRIAM-1M, PWI experiments were extensively carried out and hydrogen recycling and the related PWI phenomena were studied. The global wall pumping rate was estimated using a global particle balance model. The wall temperature plays an important role of the hydrogen reemission of the wall. In the case of the low temperature wall, no wall saturation was observed until the ultra-long discharge with the duration of 5 h 16 min. At that time, continuous growth of the deposited layer was observed. Co-deposition of hydrogen with molybdenum seems to attribute to the continuous wall pumping. The wall pumping rate, which is estimated from the total amount
of hydrogen retention in the co-deposits and the discharge duration, is consistent with the wall pumping rate estimated from the global particle balance.

On the basis of results and knowledge in TRIAM-1M, the new spherical tokamak QUEST is constructing as academic basis research on steady state operation and its relating physics.

REFERENCES