**Progress of High-Performance Steady-State Plasma and Critical PWI issue in the LHD**


National Institute for Fusion Science, 322-6, Oroshi-cho, Toki-city, 509-5292, Japan
*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan
**Graduate School of Engineering, Osaka University, 2-1, Yamadaoka, Suita, Osaka, 565-0871, Japan
E-mail contact of main author: kasahara.hiroshi@LHD.nifs.ac.jp

**Abstract.**

An ultra-long-pulse plasma with a duration time ($\tau_d$) of 48 min, a line-averaged electron density ($n_{e0}$) of 1.2x10^{19} m^{-3}, and electron and ion temperatures ($T_{e0}, T_{i0}$) of 2 keV have been achieved by the averaged heating power ($P_{\text{ICH-ECH}}$) of 1.2 MW and a proportional-integral-derivative (PID) control of particle fueling in the LHD. The heating energy injected into plasma ($W_{\text{heat}}$) reached 3.36 GJ, which is a new world record in toroidal plasmas. The ultra-long-pulse plasmas are often terminated by a sudden increase in carbon impurity, which might be caused by ejection of the carbon-rich mixed-material deposition layers with a small amount of Fe elements (~ a few %) on the plasma facing surface (PFS). A large amount of mixed-material layers, consisting mainly of carbon (> 90%) and iron impurities, are formed over a wide surface area of the PFS. Carbon impurity originally from the divertor region (domes and divertor plates) and iron impurity from the first wall by physical sputtering are deposited on the PFS during the steady-state operation (SSO). On the PFS, helium radiation damage is also created just under the mixed-material deposition layers, and they increase retention of helium. Such a long deposition process plays an important role of sudden impurity source causing the particle source and plasma termination in the SSO.

1. **Introduction**

In designing an attractive fusion reactor, the plasma duration must be steady state, and long-pulse plasma discharges have been investigated in various toroidal plasmas. Ultra-long pulse plasma with the duration time $\tau_d \sim 5$ hours and electron density $n_{e0} < 0.1x10^{19} m^{-3}$ and lower hybrid heating power $P_{\text{LHW}} \sim 0.05$ MW was achieved at TRIAM-1M [1], and higher-performance steady-state plasmas with $\tau_d \sim 6$ min, $n_{e0} \sim 2x10^{19} m^{-3}$ and $P_{\text{LHW}} \sim 3$ MW was demonstrated on Tore Supra [2]. In order to sustain steady-state plasma in these experiments, lower hybrid wave (LHW) heating is a very important issue to drive the plasma current, and steady state operation with higher-performance was limited by the health of LHW heating devices and the local hot spots related to heating losses. The Large Helical Device (LHD) [3] has steady-state magnetic configuration by superconducting coils, and ultra-long pulse discharge with $\tau_d \sim 54$ min, $n_{e0} \sim 0.4x10^{19} m^{-3}$, radio-frequency heating power $P_{\text{RF}} \sim 0.5$ MW (ion cyclotron heating $P_{\text{ICH}} \sim 0.4$ MW and electron cyclotron heating $P_{\text{ECH}} \sim 0.1$ MW) was demonstrated without plasma current drive for Helium plasma [4]. Continuous Helium particle fueling was needed during the plasma duration time, and the wall pumping with relatively low temperature for the LHD was not saturated for the conditions. In fusion reactors, wall pumping seems to be negligible by the balance between particle capture and
releas, and it is necessary to sustain higher-performance plasmas with $n_e > 10^{19} \text{ m}^{-3}$, $T_e \approx T_i > a \text{ few keV}$, and heating power $\approx a \text{ few MW}$ for several thousand seconds at the least.

2. Improving Steady-state Heating Devices and the Feedback Controls

In order to sustain higher-performance plasmas, the improvements of high power steady-state heating devices [5], the integration of plasma operation, and the modification of divertor configuration have been performed in the LHD. Main high power steady-state heating is carried out by ICH with Hydrogen minority regime for Helium plasmas, and three kinds of ICRF antennas, a hand shake from antenna (HAS) at the 3.5 port, a field aligned transforming antenna (FAIT) at the 4.5 port and a poloidal array antenna (PA) at the 7.5 port, are installed at different toroidal sections as shown in Fig. 1. There were several particle-fueling methods, such as mass-flow controller (MFC), piezo-valve, super-sonic gas puffing (SSGP), and hydrogen pellet, and Helium and Hydrogen fueling was suitably carried out by several feedback controls.

Figure 1 shows the schematic view of the particle control system, the integrating heating power control system and ICH power control system for steady-state operation. These systems were communicated to each other, synchronously. When the electron temperature around the plasma edge with $\rho \approx 0.8$ rapidly falls by the unintended impurity mixing, the heating power boosting and emergent particle fueling stop were conducted at the same time. Then plasma temperature and electron density could be kept constant, and steady-state plasma duration was easily extended. The integrating plasma operation, the increasing steady-state heating power for ICH, and center focused electron heating using 154 GHz enabled higher-performance steady-state operation, and robust plasma discharges were achieved.
In order to estimate the suitable gas-fueling rate with the time evolution of the wall-pumping rate, a PID control was very useful to adopt to the slow changes of wall-pumping rate, and the gradual density rising after $t \sim 1000$ sec was negligible using the new particle fueling rate methods. Because a small overestimation of gas-fueling rate easily raises electron density, accurately small amounts of gas-fueling rate was a critical issue for sustaining long-pulse plasma discharge.

3. Ultra-long Pulse Plasma Discharge with $n_e \sim 10^{19}$ m$^{-3}$, $T_e \sim T_i \sim 2$ keV and $P_{RF} \sim 1$ MW

Steady-state plasma duration with $\tau_d >$ several tens of minutes, $n_{e0} \sim 10^{19}$ m$^{-3}$ and $P_{RF}$ a few MW was demonstrated by improving heating quality of ICH, increasing the RF heating power, and operating adequate gas-fueling with time evolution of the wall-recycling rate. In the LHD, the study of steady-state experiment reaches new regions with the weak wall-pumping region with low temperature and higher-performance plasma parameters.

3.1. High-performance Long-pulse Plasma Discharges without Current Drive

Figure 2 shows the higher-performance ultra-long plasma duration with the line-averaged electron density $n_{e0} \sim 1.2 \times 10^{19}$ m$^{-3}$, ion and electron temperature $T_{i0} \sim T_{e0} \sim 2$ keV, $P_{RF} \sim 1.2$ MW ($P_{ICH} \sim 0.94$ MW and $P_{ECH} \sim 0.26$ MW), and $\tau_d \sim 2859$ sec for helium plasma on the Hydrogen minority regime. In order to maintain the minority ratio of Hydrogen, two kinds of Hydrogen fueling methods were used. The first method was the short-pulse gas puffing at 9I port, and the second method was super-sonic gas puffing (SSGP) at 3.5L port. The SSGP was installed close to the HAS antenna. Then the minority ratio inside of the vacuum vessel was
kept constant under the 10% during steady-state operation. Total radiation power $P_{\text{rad}}$ measured by bolometer in Fig. 2 (c) was kept constant, and the impurity accumulation with $\tau_d \sim 48$ min was not observed in the LHD. However, the spike frequency of line intensity of the carbon spectrum was clearly increased after long-pulse plasma durations, and then strong emission around the plasma edge was easily observed. That rapid density rising was consistent with the spikes of the carbon line spectrum was clearly observed, and in the former ultra-long pulse discharge with $P_{\text{RF}} \sim 0.5$ MW and $\tau_d \sim 54$ min a few spikes were consistent with density rising events [4]. Boosting RF heating power worked effectively during the ultra-long pulse plasma, and plasma was robustly sustained at the rapid density increasing events $t \sim 500$ sec and 1400 sec in Fig. 2. On the former high-performance steady-state operation with $n_{e0} \sim 1 \times 10^{19}$ m$^{-3}$ and $P_{\text{RF}} \sim 1$ MW [5], electron density could not keep constant by the overestimating particle fueling rate, and the electron density was kept constant by the accurate particle fueling rate estimated by a real-time PID algorithm.

3.2. Time Evolution of Helium Gas-fueling Rate in Two Different Pumping Conditions for a Cryosorption Pump (cryo pump)

Figure 3 shows the time evolutions in various fueling parameters for two long-pulse discharges ($\tau_d > 40$ min) with the difference of cryo pump condition for Helium, just after refreshed cryo pump (#124576) and relatively saturated cryo pump (#124579). In these discharges, electron densities ($n_e \sim 1 \times 10^{19}$ m$^{-3}$) were kept constant, and the averaged RF heating powers were approximately the same ($P_{\text{RF}} \sim 1.2$MW). Total neutral gas pressure and the ratio of main particles inside the vacuum vessel were kept constant during these discharges, and the main gas component was Helium with the ratio > 90% against total pressures. The second component of one was Hydrogen with the ratio ~ 10%, and the other species were less than a few %. Figure 3 (b) shows that the amount of total fuelled Helium particles and the fueling rate, (c) typical gas contents inside the vacuum vessel, and (d) Helium pressures during long-pulse discharges with $\tau_d > 40$ min.

FIG. 3. Time evolution of gas-fueling and main contents of particles inside of vacuum vessel during long-pulse plasma durations. (a) a line-averaged electron density ($n_e$), (b) fuelled He particles and the fueling rate, (c) typical gas contents inside the vacuum vessel, and (d) Helium pressures during long-pulse discharges with $\tau_d > 40$ min.
2.5x10^{19} \text{ He/s}) in \ t \sim 1500 \text{ sec (phase III). The gas-fueling rate was recovered, but the plasma parameters were same in phase II and phase III. These behaviours were first observed on the high-performance ultra-long plasma operation with } P_{\text{RF}} \sim \text{ a few MW and a large amount of fuelled particles and } \tau_\text{d} \sim \text{ several dozen minutes in the LHD, and one of the steady-state plasma duration oriented issues appeared.} \text{ The time-scales of Temperatures and the Averaged Heating Power to Divertor Plates in Various Toroidal Sections}

Figure 4 shows typical temperatures of main components in the vacuum vessel. The time evolution of these temperatures are fitted to the exponential function of equation (1) as follows:
\[ T(t) = T_0 + T_{sat} \left( 1 - e^{-t/\tau_{sat}} \right), \]  

where \( T_0 \) is initial temperature at \( t \approx 0 \) sec and \( T_{sat} + \tau_{sat} \) is the saturation temperature at \( t \approx \infty \) sec. The \( \tau_{sat} \) means the time-scale of saturation temperatures, and the \( \tau_{sat} \) is one of the indicators for thermal saturation. The longest time-scale was approximately \( \tau_{sat} \approx 1300 \) sec at the first wall, and the maximum temperature of first wall was observed around the divertor plates with relatively high heat flux. The \( \tau_{sat} \) of the surface temperature for the open divertor plate at 3I port and of the thermocouple installed below one cm from the divertor surface were approximately 200 sec and 100 sec. Maximum temperature (\( \sim 1200 \) K) was observed at the surface of the ICRF antenna protector for the PA antenna, and the time-scale (\( \tau_{sat} \approx 212 \) sec) was similar to the time-scale (\( \tau_{sat} \approx 170 \) sec) of the divertor surface.

Figure 4 (d) shows the averaged heating power of divertor plates calculated from the water-cooling power of divertor plates in various toroidal sections. The total averaged heating power of divertor plates was approximately 0.67 MW, and the power ratio against the heating power was approximately 56%. The total cross section of the footprint on the surface for divertor plates \( (S_{footprint}) \) was \( \sim 2 \) m\(^2\) [6], and the averaged divertor heat flux with the footprint width of 1 cm was approximately 0.33 MW/m\(^2\) with \( P_{RF} \sim 1.2 \) MW. Though RF heating power for ICH was evenly injected using the HAS antenna, the FAIT antenna, and the PA antenna, the divertor heating power and the local hot spot temperature around the PA antenna was relatively higher than the other antennas. The local heating power of divertor seems to be caused by fast wave heating quality and the local hot spots [5, 7].

Figure 5 shows the calculation results using actual three-dimensional divertor model assembled from two blocks of carbon-fiber-composite (CFC) parts with the uniformity heat flux \( I_{heat} \sim 0.36 \) MW/m\(^2\) on the footprints width \( \sim 1 \) cm to evaluate at the experimental heat flux on the surface of the open divertor plate. The surface temperature contacting a water-cooling pipe was fixed to 50 degC, and radiative condition was set around the surface of the divertor plates with no radiation reflection. Comparing the actual surface temperature of the divertor plate (\( \sim 460 \) degC) in Fig. 4 (a) with the predicted surface temperature (\( \sim 75 \) degC) with the \( I_{heat} \sim 0.36 \) MW/m\(^2\) in Fig. 5, actual divertor heat flux seems to be much higher than averaged heat flux. If this calculation result of surface temperature is correct, the \( I_{heat} \) must be 6 MW/m\(^2\) with 18 times higher than averaged heat flux \( \sim 0.33 \) MW/m\(^2\). On the other hand, this open divertor model is similar to the helical divertor plates. From the resulting thermocouple temperature, the closed helical divertor plate with relatively large heat flux (L5) with \( P_{RF} \sim 1.2 \) MW seems to be \( I_{heat} \sim 3 \) MW/m\(^2\). In the LHD, several divertor plates were

![Figure 6](image-url)  

**FIG. 6.** Strong flashes of carbon impurity around the plasma edge near divertor plates after \( t \approx 2800 \) sec (left figure) and the history of the time evolution and the repeated long-pulse discharges for summarizing the intensity of the carbon line spectrum for every 100 sec (right figure).
strongly concentrated with large heat flux (3 ~ 6 MW/m$^2$), and the large heat flux operation predicted on ITER long-pulse operation ($\tau_d \sim 1000$ sec and $\Gamma_{\text{heat}} \sim 5$ MW/m$^2$) already seems to be achieved on the ultra-long pulse discharge with $\tau_d \sim 2859$ sec and $P_{\text{RF}} \sim 1.2$ MW in the LHD.

3.3. Increasing the Spike Frequency for the Intensity of Carbon Line Spectrum and the Growth Rate of Mixed-material Layer only Exposed Long-Pulse Discharges

The left image in Fig. 6 shows the strong flashes of carbon impurity around the plasma edge near the closed helical divertor plates with relatively large heat flux (\sim a few MW/m$^2$) measured by a fast camera. And the right figure in Fig. 6 shows the history of time evolution and the repeated long-pulse discharges for summarizing the spike intensity of carbon line spectrum for every 100 sec on the long-pulse discharges. When the increasing RF heating power with higher density plasma and the extending plasma duration time are improved, flashes and sparks were easily observed with low total radiation level such as in Fig. 2 (c). However, the intensity of the flashes was gradually increased, and the spike frequency of the carbon line spectrum was clearly increased. Before steady-state plasma operation with $\tau_d > 10$ min, the level of spike frequencies and magnitude of carbon line spectrum was similar to the behavior before 500 sec in Fig. 2. The summarized spike intensity of the carbon line spectrum in Figure 6 (right) for #124530 was small, but there were many repeated short-pulse discharges with $t_d \sim 3$ sec and plasma heating power $P_{\text{heat}} \sim 30$ MW. Total plasma duration time for short-pulse discharges before steady-state operation was much longer than $\tau_d \sim 200$ min, but it did not clearly affect the intensity of carbon. After continuous long-pulse discharges with $\tau_d > 10$ min, the spike frequency and the magnitude of carbon line spectrum were clearly increased in Fig. 6 (right). After the experimental campaign, large amounts of mixed-material layer and flakes were observed everywhere in the vacuum vessel, and the layers was strongly grew around the particular divertor plates with relatively high heat flux and geometrically dense region. The main component of the mixed-material layer is carbon (> 90 %) with a small amount of Fe element, and the component of divertor plates is carbon in the LHD.

In order to study the mixed-material layer produced by long-pulse plasma durations, a stainless steel specimen (SUS316L) was located on the equivalent position of the first wall surface, as shown in Fig. 7 (a), and the specimen was only exposed to the long-pulse discharges for Helium plasma with $n_0 \sim 10^{19}$ m$^{-3}$, $T_0 \sim T_i \sim 2$ keV, and $P_{\text{RF}} \sim 1$ MW in
Figure 7 (b) shows the TEM picture of the specimen with the exposure time $\tau_{\text{exp}} \sim 1000$ sec and the schematic view. The thickness of deposition layer on the surface of the specimen was increased under continuous heat and particle fluxes with an increase in steady-state plasma duration. Majority composition of the deposition layer was carbon (> 98%), and a few % of Fe element was observed. In earlier studies of the impurity transport and formation of the mixed-material, these thick deposition layers were observed in particular dome plates near the divertor [8]. Thus, the short-range transport of the carbon impurity from divertor plates plays an important role for the formation of a carbon-rich mixed-material deposition layer. Since such layers are hard and brittle, deposition layers are easily exfoliated as a flake. In the ultra-long-pulse discharge, the plasma termination process was followed by a large amount of mixed-material ejection from near the dome plates, locally. During strong flashes, the line intensity of the carbon spectrum was increased as many as 30 ~ 40 times, and finally became 100 times as large.

We find that the mixed-material deposition layer and the damaged region can easily retain helium particles, and these trapped particles are released below 400 K. The amount of trapped particles by both layers is proportional to these thicknesses and exposure time such as is shown in Fig. 7 (c). In the ultra-long-pulse discharge, the amount of fueled particles of He is approximately $3.7 \times 10^{22}$ (atom) for $t_d \sim 48$ min. Assuming that these layers cover of the 1/10 surface of the vacuum vessel and the divertor, the maximum amount of trapped He particles by these layers is evaluated as $1.1 \times 10^{22}$ atom. Since such an amount of He trapped particles is 100 times as large as that of plasma and neutral particles in the vacuum vessel, the release of He cannot be negligible in the wall-temperature increasing phase. In order to avoid large carbon impurity causing plasma termination and to maintain a global particle balance, control of the growth rate of the deposition layer is required in steady-state devices. This will be a critical issue in steady-state devices and long-term plasma operation such as a fusion reactor.

4. Summary

Higher-performance steady-state plasma could be easily sustained by the development of steady-state heating devices. The ultra-long pulse plasma with $n_{e0} \sim 1.2 \times 10^{19}$ m$^{-3}$, $T_{e0} \sim T_{i0} \sim 2$keV, $\tau_d \sim 2859$ sec, and $P_{RF} \sim 1.2$MW was achieved, and total ejection energy reached 3.36 GJ. By increasing the plasma temperature, long-pulse plasmas became robust, but high spike frequencies of carbon line spectrum and the thick mixed-material layers were observed. The layer can be trappable the He particles, and the trapped particles are easily released under 400 K.

References