The progress of study of steady-state discharge for helical plasma and its international collaboration
ヘリカルプラズマにおける高性能定常放電の進展と国際協力

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An ultra-long-pulse plasma with a duration time of 48 min, a line-averaged electron density of 1.2x10^{19} m^{-3}, and electron and ion temperatures (T_{e0}, T_i) of 2 keV has been achieved by the averaged heating power ($P_{ICH+ECH}$) of 1.2 MW. The ultra-long-pulse plasmas are often terminated by a sudden increase in carbon impurity, which might be caused by entrance of mixed-material deposition layers 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 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

Long-pule plasma duration is one of the most important issues for the realizing commercial fusion reactor, and long-pulse discharges with plasma duration time over a couple ten minutes have been investigated in the Large Helical Device (LHD) using helical plasmas. In LHD, only superconducting coils without current drive will fulfill magnetic configuration, and it is great advantage to maintain plasma duration.

2. Extending the operation region of long-pulse plasma duration

The high-performance plasma experiments with a line-averaged electron density (n_e) > 1x10^{19} m^{-3} and T_e > a few keV have been investigated in order to understand PWI effect on a long time scale (> a few thousand seconds) in LHD. Figure 1 shows an ultra-long-pulse plasma discharge of a helium plasma with n_e ~ 1.2 x10^{19} m^{-3}, T_e ~ T_i ~ 2keV, P_{RF} ~ 1.2 MW (P_{ICH} ~ 0.9MW, P_{ECH} ~ 0.3MW), and duration time ~ 2,859 sec. The newly achieved heating energy of 3.36GJ is twice as the previous world record, 1.6GJ, with P_{RF} ~ 0.5MW and n_e ~

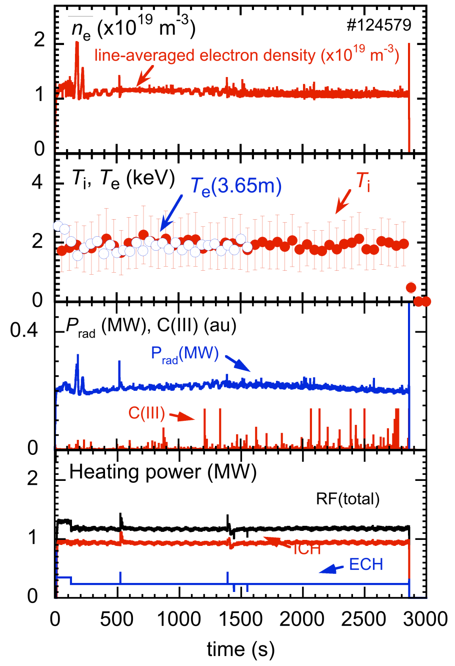

Fig. 1 Helium discharge waveform in hydrogen minority regime.

$0.4\mathrm{x}10^{19}$ m^{-3} in LHD [1]. Three types of ICRF antennas were installed at different toroidal sections in order to avoid local hot spots around each ICRF antenna. Real-time feedback control for impedance matching, antenna phasing and heating power boosting for unexpected impurity influx were also developed. These heating techniques enabled stable plasma heating. In early long-pulse discharge with the duration time ~ 19 min with similar plasma performance, electron density rose due to overestimate gas-fueling rate [2]. The overestimation of gas-fueling rate, which was strongly related to time evolution of wall-pumping rate, was observed around duration tiem > 1000 sec. In the last campaign, a proportional-integral-derivative control method was used to maintain a constant level of the plasma density, and plasma duration time reached 48 min. Radiation power (P_{rad}) was less than approximately 17 % of P_{RF}, where the carbon and iron impurity accumulation was negligible in the discharge. The spike frequency of the line intensity for the carbon spectrum began to increase after 600 sec. At that time, the divertor temperature was almost saturated at 460 ºC. Many flashes are observed with a monitor TV camera which views mostly outside of LCFS and the divertor region. These flashes are not always synchronized to spikes in total radiation and line intensities in impurity spectra. It may be caused by exfoliation of the mixed-material layers and initiation of the arcs. Both the frequency and intensity are increased as the discharge time goes on, which suggest that a large size of carbon mixed-material layers on dome plates near divertors are ejected into the plasma. The ultra-long-pulse plasma was terminated within 0.1 ~ 0.2 sec, where the radiation power fraction reached 38 % of P_{RF}. This suggests that it is very important to analyze mixed-material layers and understand the growth mechanism in the ultra-long-pulse plasma operation.

3. Growing mixed-material layer by the Title

The Figure 2 shows the cross-sectional transmission electron microscope (TEM) image of the stainless steel specimen (SUS316L) and corresponding schematic view of the microstructural modifications such as bubbles and deposition layer. The mixed-material deposition layer with the thickness of ~ 5 nm was formed on the top surface. In addition, fine He bubbles with size of 2-3 nm were densely formed on SUS316L matrix just under the deposition layer at the same time. This specimen was located on the equivalent position of the first wall surface, and it was exposed to SSO discharges up to duration time ~ 1000 sec. The thickness of deposition layer was increased under continuous heat and particle fluxes with an increase in steady-state plasma duration. Majority composition of the deposition layer was carbon (>90%), and a few % of Fe element was observed. In the previous studies of the impurity transport and formation of the mixed-material, these thick deposition layers were observed in particular dome plates near the divertor [3]. Thus, the short-range transport of the carbon impurity from divertor plates plays an important role for the formation of carbon rich mixed-material deposition layer. Since such layers are hard and brittle, deposition layers are easily removed as a flake. In the ultra-long-pulse discharge for helium plasma, the plasma termination process was followed by large amount of mixed-material ejection from near dome plates, locally. During strong flashes, the line intensity of carbon spectrum was increased largely 30 ~ 40 times, and finally became 100 times large. The frequency of Carbon III emission was clearly increased just after long-pulse discharge with the duration time of 30 min for helium plasma rather than after repeated high-power short pulse operation for hydrogen plasma using NBI. Through the international collaborations in steady-state devices, we have to assess the mixed-material effect to each other, and it will be more important issues for fusion reactors.

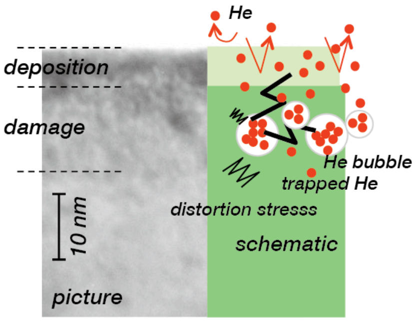

Fig. 2 Cross-sectional TEM image of the stainless steal specimen after only exposer to SSO discharge (1000 sec) at the first wall equivalent position.

Acknowledgments

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References

[1] T. Mutoh et al.: Nucl Fusion **53** (2013) 063017.
[2] H. Kasahara te al,: Phys. Plasmas **21** (2014) 57.
[3] M. Tokitani et al.: J. Nucl. Mater. **438** (2013) S818.