18pA2-4

Progress in High Performance Steady State Plasma Operation in LHD
LHDにおける高性能プラズマ定常維持実験の進展

Yasuo Yoshimura, Hiroshi Kasahara, Masayuki Tokitani, Naoko Ashikawa,
Yoshio Ueda, Kazunobu Nagasaki, *et al.*
吉村泰夫、笠原寛史、時谷政行、芦川直子、上田良夫[1)]、長崎百伸[2)]、関哲夫、斉藤健二、關良輔、神尾修治、野村吾郎、久保伸、下妻隆、伊神弘恵、高橋裕己、伊井亨、小林策治、伊藤哲、水野嘉識、岡田宏太、庄司主、田中謙治、田中宏彦、土屋隼人、徳沢季彦、牧野良平、増崎貴、宮澤順一、本島厳、山田一博、武藤敬、山田弘司、竹入康彦、小森彰夫

National Institute for Fusion Science, 322-6, Toki, Gifu 509-5292, Japan
核融合科学研究所 〒509-5292　岐阜県土岐市下石町 322-6
1) Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan
2) Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan

In the 17th experimental campaign of LHD in 2013, steady state operation of high performance plasmas made a huge progress. A discharge with the line average electron density of 1.2×10^{19} m^{-3} and the central electron and ion temperatures of 2 keV was sustained for 48 min. by the heating power of 1.2 MW. The extension of the duration time from the previous record, 19 min. of a discharge with nearly the same parameters, was achieved by improvements of the heating devices and the gas fueling system. The progress in the plasma duration time with this plasma parameter range revealed a new aspect of the state of the plasma-facing surface. At the beginning of the start of a plasma discharge, the wall is in the pumping phase, and the pumping phase gradually transitions to the saturation phase by ~10 min. Then the second wall-pumping phase appears at about half an hour from the start of the discharges, following to the saturation phase.

1. Introduction

Recent years, improvement in plasma parameters of long-pulse discharges in the LHD, specifically, the discharges with $n_{\mathrm{e\_ave}}$ of over 1×10^{19} m^{-3} and T_{e0} of over 1 keV as a basic objective, has been attempted by applying higher heating power. As the first step of the improvement, a 19 min. discharge with $n_{\mathrm{e\_ave}}$ of 1×10^{19} m^{-3} and T_{e0} of 2.5 keV with P_{heat} of ~1 MW by ICH (720 kW) and ECH (260 kW) was achieved in the LHD 16th experimental campaign in 2012 [1].

This paper describes a progress in high performance steady state operation obtained in the LHD 17th experimental campaign in 2013. The improvements of the heating devices and the gas fueling system after the 16th campaign enabled the progress.

2. Upgrade of Heating Devices

2.1 *ICH system*

A pair of ICH antennas was newly installed at the LHD 4.5-U and L ports so that the number of ICH antennas increased from 4 to 6. The installation of the new antennas improved not only the total heating power but also the stability of each antenna due to the ability of reduction of the power per antenna, not reducing the total heating power from that of the previous system.

Restoration scheme of the power supply from a discontinuation, due to interlock function detecting excessive reflected power to the system and/or voltage on the system, was modified to be automatic by judging measured data within dozens of milliseconds. Reduction of the heating power for a few seconds causes an increase in the electron density and a termination of the discharge.

2.2 *ECH system*

The EC-wave power sources available for the long-pulse operation in the 16th campaign were two 77 and one 84 GHz gyrotrons. However, the 77 GHz gyrotrons suffered gradual increase in the internal pressure so that the continuous operation time was limited up to about 10 min. For the 19 min. discharge, the two 77 GHz gyrotrons were operated alternately with the intervals of 2 min.

In the 17th campaign, a new 154 GHz gyrotron [2] was applied for long-pulse discharges. The 154 GHz gyrotron furnishes a sub-window on it to remove inner stray radiation. Also, the high frequency, that is, short wavelength reduces the diffraction of the waves inside the gyrotron. No serious increase in the inside pressure occurs during long-pulse operation.

3. Upgrade of Gas Fueling System

A newly constructed gas fueling system was applied for long-pulse discharges. It furnishes mass flow controllers and FPGA control software to make the collect feedback control of the electron density and collect evaluation of the amount of the fed gas available even when the required flow rate is low. The piezo-valve used for the previous gas fueling system worked non-linearly in the low gas flow rate range, and even when the control voltage was set zero, gradual increase in the electron density could not suppressed.

4. Achievement of High Performance 48 Min. Discharge and the New Aspect of the State of Plasma Facing Surface

Figure 1 shows the waveforms obtained in the achieved 48 min. discharge [3]. P_{heat} in total of ~1.2 MW by ICH (940 kW from 6 antennas) and ECH (120 kW each from 154 GHz and 84 GHz gyrotrons) was applied steadily. The target n_{e_ave} of 1.2×10^{19} m^{-3} was set on the gas fueling system, so that n_{e_ave} of ~1.2×10^{19} m^{-3} was kept during the discharge. Both the T_{e0} and T_{i0} were also kept at the constant value, ~2 keV. Thus, the improvements of the heating devices and gas fueling system worked quite well and made the high performance steady state operation possible in the LHD. The cause of the termination of the discharge was intense irruptions of carbon flakes from the divertor tiles.

The progress in the plasma parameter in the long pulse discharges in the recent LHD experiments is summarized in Fig. 2, together with the data from TRIAM-1M [4, 5], EAST [6] and Tore Supra [7]. The horizontal axis is total injected energy in the discharges and the vertical axis is a product of n_{e_ave}, T_{e0} and plasma duration time as a measure of the compatible achievements of high plasma parameter and long duration time. The significant progress of the high performance 48 min. discharge (#124579) is seen.

Those discharges revealed a new aspect of the state of the plasma-facing surface. As seen in Fig. 1 (c), Helium gas fueling was required after the time of t ~ 1,400 s to keep n_{e_ave} at 1.1×10^{19} m^{-3}, while negligibly low gas fueling was needed during 300 ~ 1,400 s to keep the same density. This indicates an appearance of the 2nd wall-pumping phase after the saturation phase. So far the mechanism of this phenomenon is not clear, but accumulation of mixed-material layer, which is mainly composed of carbon, on the plasma-facing surface [8] would play an important role.

Acknowledgments

The authors would like to express their thanks to NIFS staff for performing the LHD experiments. This work was supported by the LHD project (NIFS ULRR701, 703, 801, 804, 806, KLPR016, KUGM051).

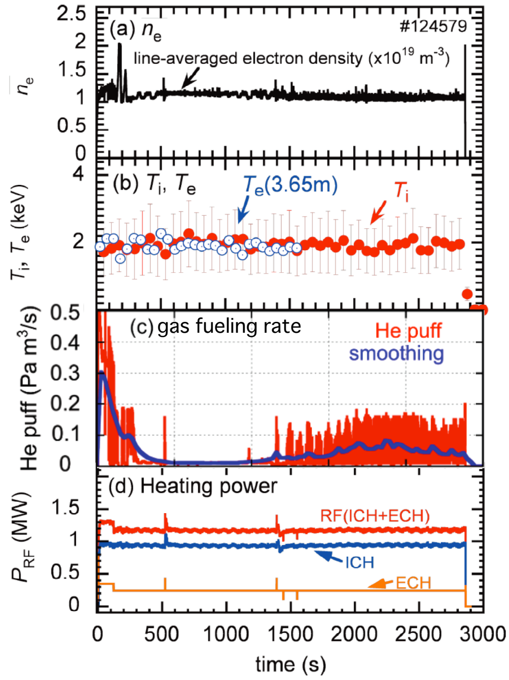

Fig. 1 Waveforms in the high performance 48 min. (2859 s) discharge #124579.

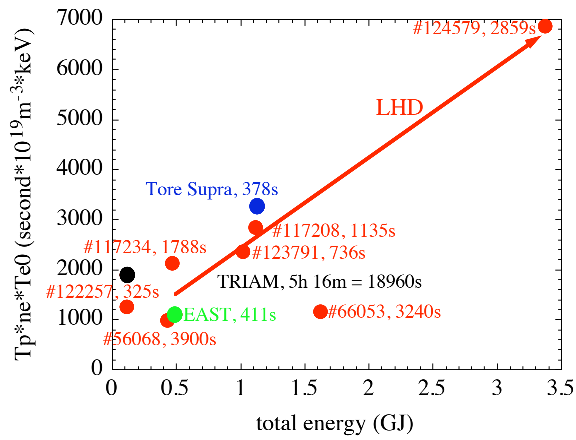

Fig. 2 Compatible progresses in the plasma parameter, applied power and plasma duration time in the LHD.

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