Extending the Total Neutron Emission Rate of Steady-state Deuterium Large Helical Plasma Guided by a Data-driven Approach

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Abstract

A trial for extending the total neutron emission rate (S_n) was performed in the Large Helical Device (LHD) deuterium plasma experiment using a gas puff in order to show the way to realize a steady-state fusion reactor. In the 22nd experimental campaign of the LHD, a high S_n discharge was performed by the experimental scenario guided by a data-driven approach. A regression analysis of S_n was conducted beforehand using the externally controllable parameters based on the database of the previous three campaigns. Then, the high S_n record was successfully updated to be 3.7×10^{15} n/s in a steady-state discharge during the 22nd campaign in line with the regression expression. This study demonstrates that such a data-driven approach is effective for the gradual extension of S_n beyond the employed database.

Keywords: LHD, Deuterium experiment, Total neutron emission rate, data-driven approach, steady-

state plasmas

1. Introduction

The development of high-performance plasmas has been focused on currently running fusion plasma experiments to show the way toward a fusion reactor. There are a variety of plasma parameters, such as the ion temperature, the triple product, the plasma beta, and the fusion output. The fusion output is one of the most critical parameters in evaluating the reach toward a fusion burning plasma because electrical power will be generated by the energy of deuterium-tritium fusion neutrons absorbed by the blanket modules. At the same time, a method of controlling the fusion performance technique should be developed to control the energy output from a fusion reactor. In previous deuterium experiments performed in large tokamaks, a total neutron emission rate (S_n) of over 5×10^{16} n/s was achieved [1-3]. For S_n prediction, empirical formula techniques were introduced in JET in order to adjust the aperture to avoid the saturation of the pulse counting rate in the neutron cameras in advance of discharges [4]. For helical devices, which have the advantage of steady-state operation over tokamaks, the performance of a fusion plasma in a relatively large-sized machine has been investigated in the Large Helical Device (LHD) [5] and Wendelstein 7-X [6]. The deuterium experiment in LHD was initiated in 2017 [7]. In the deuterium operation of LHD, the neutron emission from the so-called beam-thermal reaction is dominant [8, 9]. Therefore, by using comprehensive

neutron diagnostics, studies of beam ion confinement are advanced in LHD [10-23].

Investigation of S_n dependence on the magnetic configuration and the plasma density has been performed in the deuterium operation in LHD [10, 11]. It was found that a relatively high S_n is obtained in the vacuum magnetic axis position (R_{ax}) of 3.55 m, the toroidal magnetic field strength (B_t) of 2.89 T, and the line-averaged electron density (n_{e_avg}) of 2×10^{19}m^{-3} to 3×10^{19}m^{-3} [11, 24, 25]. For a high S_n discharge, the record of S_n in steady-state discharge using a gas puff was found to be ~3.1×10^{15} n/s in the 19th campaign of the LHD experiment, which was the LHD's first deuterium campaign that used intensive electron cyclotron heating (ECH) and neutral beam (NB) injections. In the 22nd LHD campaign performed in FY2020, the guidance deduces because the data-driven approach was applied to consider a high S_n discharge scenario. Here, the data-driven approach is classified into a complementary method of the physics-based approach without physics considerations. The regression analysis for S_n values, which used the externally controllable parameters obtained during the 19th and 21st LHD campaigns, such as the line-averaged electron density and injection power of NB injections, was utilized to inspect the importance of each controllable parameter for achieving a high S_n [26] before starting 22nd campaign. This was the same approach used to obtain the regression expression for the thermal diffusivities in LHD [27]. This approach may be appropriate for controlling the fusion output in a fusion reactor in the future. This paper represents the extension of high S_n in LHD, guided by a regression approach.

2. Regression approach for the evaluation of parameter importance

High S_n discharge was performed using the full power heating of ECH, a negative ion-based neutral beam (N-NB), and a positive ion-based neutral beam (P-NB) during the 19th and 21st campaigns of the LHD experiment. In this regression analysis, the experimental data points satisfying the following general restrictions were sampled. (1) The experiment was conducted in the best magnetic configuration for high S_n that is B_t of 2.89 T, and R_{ax} of 3.55 m. (2) A discharge was performed using a deuterium gas puff. (3) Both N-NB and P-NB were injected deuterium beam without a breakdown or an unintended stop. (4) Plasma was deuterium dominant, e.g., the ratio of Dα to Hα intensities measured by visible spectroscopy [28] was above 90%. (5) To avoid the period of weak NB absorption, the timing is after 500 ms from the plasma initiation. Figure 1 shows the density dependence of S_n obtained during the 19th and 21st LHD campaigns. Here, S_n was measured using the neutron flux monitor [29, 30], and n_{e_avg} was measured by a far-infrared interferometer [31]. Datasets were created at each timing for Thomson scattering diagnostics [32], that is, at intervals of 33 ms. The envelope of S_n shows that there is a peak of S_n at n_{e_avg} of 2×10^{19}-3×10^{19}m^{-3}. The steep increase of S_n in the relatively low n_{e_avg} range is due to the improvement of beam-ion deposition, and the gradual decrease of S_n in the relatively high n_{e_avg} region is due to the decrease of the electron temperature, which induces low beam-ion density because of the shorter slowing-down time [9, 11]. For the

regression analysis, the range of n_{e_avg} of 1×10^{19}-3×10^{19} m^{-3}, where the promising region of updating high S_n in steady-state discharge, was selected. Here, in this dataset, the injection power ranges of N-NB ($P_{N\text{-}NB}$), P-NB ($P_{P\text{-}NB}$), and ECH (P_{ECH}) were 1.3 MW to 6 MW, 1.9 MW to 19 MW, and 1.0 MW to 3.8 MW, respectively. The total number of data points was 1590 from 443 available discharges. The regression analysis of S_n using only externally controllable parameters, e.g., n_{e_avg} [$10^{19}m^{-3}$], $P_{N\text{-}NB}$ [MW], $P_{P\text{-}NB}$ [MW], and P_{ECH} [MW], were conducted to identify the critical parameters for achieving high S_n. To find the regression expression, a log-linear multivariate regression was performed. The preliminary regression analysis shows $S_n = 10^{14.25} \times {n_{e\_avg}}^{0.50} \times {P_{N\text{-}NB}}^{0.73} \times {P_{P\text{-}NB}}^{0.35} \times {P_{ECH}}^{-0.07}$ with the coefficient of determination (R^2) of 0.70. For considering experimental scenarios by using a relatively small number of parameters and acquisition of better R^2, P_{ECH} was excluded from the regression analysis because of the relatively low importance of P_{ECH} compared with the other three parameters. The obtained regression expression $S_n = 10^{14.25} \times {n_{e\_avg}}^{0.52} \times {P_{N\text{-}NB}}^{0.69} \times {P_{P\text{-}NB}}^{0.37}$ shows that $P_{N\text{-}NB}$ has the largest exponent to an increase in S_n. Here, R^2 reaches 0.84 [26]. The reason for the highest exponent in $P_{N\text{-}NB}$ is that N-NB injects with relatively high energy up to 180 keV [33]. Here, the experimentally obtained S_n was 13% larger than the S_n predicted by the regression expression for the highest S_n point.

3. Update of high S_n record in steady-state discharge guided by regression analysis

High S_n discharge in the 22nd LHD campaign was performed using ECH and the ion

cyclotron range of frequency heating (ICH), N-NB, and P-NB. Table 1 shows the comparison of maximum $P_{\text{N-NB}}$ and $P_{\text{P-NB}}$ during the 19th and 21st campaigns and in the 22nd campaign. In particular, $P_{\text{N-NB}}$ increases significantly in the 22nd campaign from the previous campaigns. Here, by considering the improvements of $P_{\text{N-NB}}$ and $P_{\text{P-NB}}$, the expected increase of S_{n} in the 22nd campaign from the previous campaigns using the regression formula is approximately 10%. Figure 2 shows the waveform of the new S_{n} record discharge using a deuterium gas puff. In this discharge, P_{ECH}, the injection power of ICH, $P_{\text{N-NB}}$, and $P_{\text{P-NB}}$ increased up to 4.3 MW, up to 2.4 MW, 6.9 MW, and 19.3 MW, respectively. The central electron temperature (T_{e0}) measured by Thomson scattering diagnostics and $n_{\text{e\_avg}}$ at $t \sim 5$ s were 5.5 keV and 2.3×10^{19} m^{-3}, respectively. The time evolution of S_{n} shows that S_{n} gradually increased according to the injections of ECH, ICH, and N-NB from the beginning of the discharge and then substantially increased at $t = 4.8$ s due to P-NB injections. The highest S_{n} with 3.7×10^{15} n/s was successfully achieved at $t = 5.236$ s. Therefore, S_{n} increased by approximately 20% compared with S_{n} achieved in the previous experiment.

The experimentally obtained S_{n} data points in the 22nd campaign were compared with the S_{n} based on the regression expression, as shown in Fig. 3. Here, the open gray circles indicate the data set obtained during the 19th and 21st campaigns, and the red open circle indicates the data obtained during the 22nd campaign. Note that there are some points deviating from the diagonal dashed line in the relatively low S_{n} region. The relatively large deviation was due to the limited number of parameters used

in the regression analysis. It was found that the newly obtained S_n in the 22nd campaign relatively well aligns with the diagonal line shown in Fig. 3, despite the regression expression being applicable only in the employed database range (gray points). However, it is indicated that this regression approach is applicable as a guideline to gradually extend the S_n range beyond the employed database.

Although the regression analysis suggests that the improvement of S_n is ~10% during the 22nd campaign based on the maximum available NB injection power (Table 1), the actual improvement of S_n in the 22nd campaign experiment is ~20%. The detailed investigation of this difference is our future work. There are two possible causes of this difference. The first is the additional heating source, ECH and ICH. In this regression analysis, P_{ECH} and P_{ICH} were excluded because of the relatively low importance of P_{ECH} in the preliminary regression analysis and no ICH in high S_n discharge performed during the 19th and 21st campaigns using a gas puff. The second is that the regression expression is merely guidance without any physics considerations. Despite the relatively high coefficient of determination, there was a dissociation of S_n identified by the regression analysis of experimental results. The improved regression expression can be deduced by including measurement data such as temperature, density, and neutron profiles, and so on. However, the current expression is better at the point of the feedback to the high S_n discharge scenario.

4. Summary

A trial for extending S_n record in steady-state discharge was performed in LHD based on a data-driven approach. The regression expression of S_n using externally controllable parameters was obtained using the S_n database established during the 19th and 21st LHD experimental campaigns. Data points were selected according to the general restriction of fulfilling high S_n discharge conditions. It was found that the injection power of N-NB was more important than the line averaged density and the injection power of P-NB. In the 22nd campaign, the high S_n record in steady-state discharge was successfully updated, based on the previously deduced regression expression. The new S_n record in steady-state discharge using a deuterium gas puff is 3.7×10^{15} n/s. Even though this regression expression is valid only within the range of the database, it is demonstrated to be effective as a plausible guideline for updating the S_n record gradually beyond the current database.

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Table 1 Comparison of injection power during the 19th and 21st campaigns and the 22nd campaign in high S_n discharge. Here, $P_{N\text{-}NB}$ and $P_{P\text{-}NB}$ represent the injection power of the negative-ion-source-based neutral beam injector and the injection power of the positive-ion-source-based neutral beam injector, respectively.

Campaign	Maximum $P_{N\text{-}NB}$ (MW)	Maximum $P_{P\text{-}NB}$ (MW)
19th to 21st LHD campaigns	6.0	19.0
22nd LHD campaign	6.9	19.3

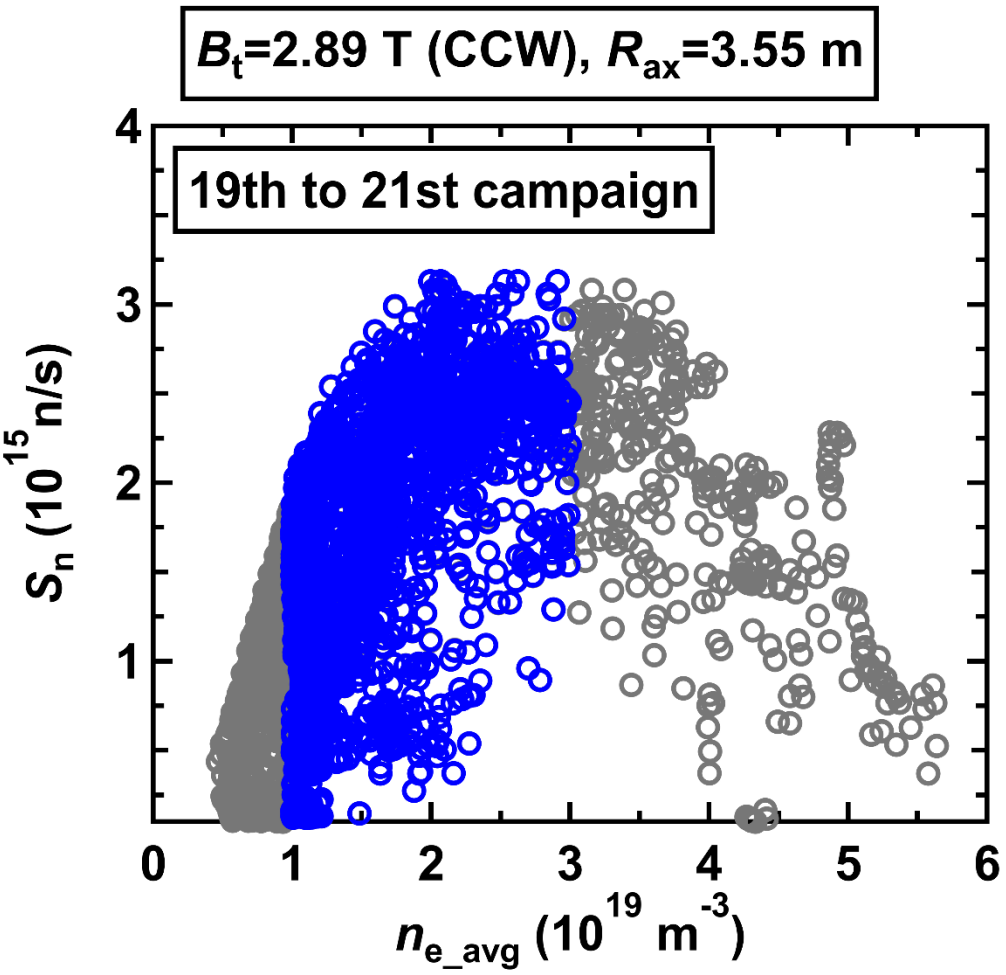

Figure 1. Total neutron emission rate (S_n) as a function of the line-averaged electron density (n_{e_avg}) obtained in steady-state discharge using a deuterium gas puff during the 19th and 21st LHD campaigns at the toroidal magnetic field strength (B_t) of 2.89 T with the counterclockwise (CCW) direction when viewing from the top and the magnetic axis position (R_{ax}) of 3.55 m. Blue open circles correspond to the data points used for the regression analysis [13].

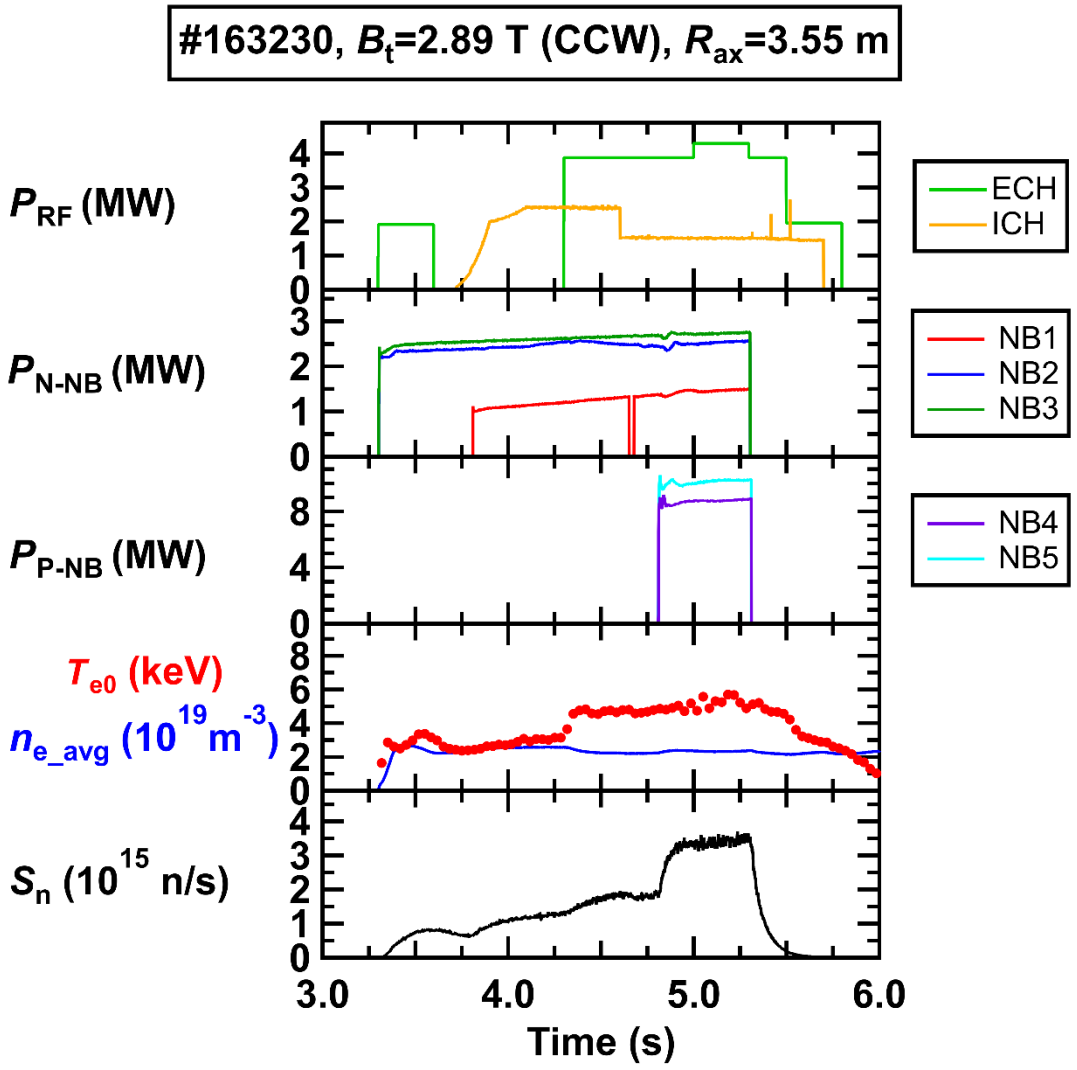

Figure 2. Maximum total neutron emission rate (S_n) discharge using a deuterium gas puff in the 22nd campaign performed at the toroidal magnetic field strength (B_t) of 2.89 T with the counterclockwise (CCW) direction when viewing from the top and the magnetic axis position (R_{ax}) of 3.55 m. Here, P_{RF}, $P_{N\text{-}NB}$, $P_{P\text{-}NB}$, T_{e0}, n_{e_avg}, ECH, ICH, and NB represent the injection power of the radiofrequency wave, the injection power of the negative-ion-source-based neutral beam injector, the injection power of the positive-ion-source-based neutral beam injector, the central electron temperature, the line-averaged

electron density, electron cyclotron heating, ion cyclotron range of frequency heating, and neutral beam injector, respectively. The obtained S_n record in steady-state deuterium discharge is 3.7×10^{15} n/s.

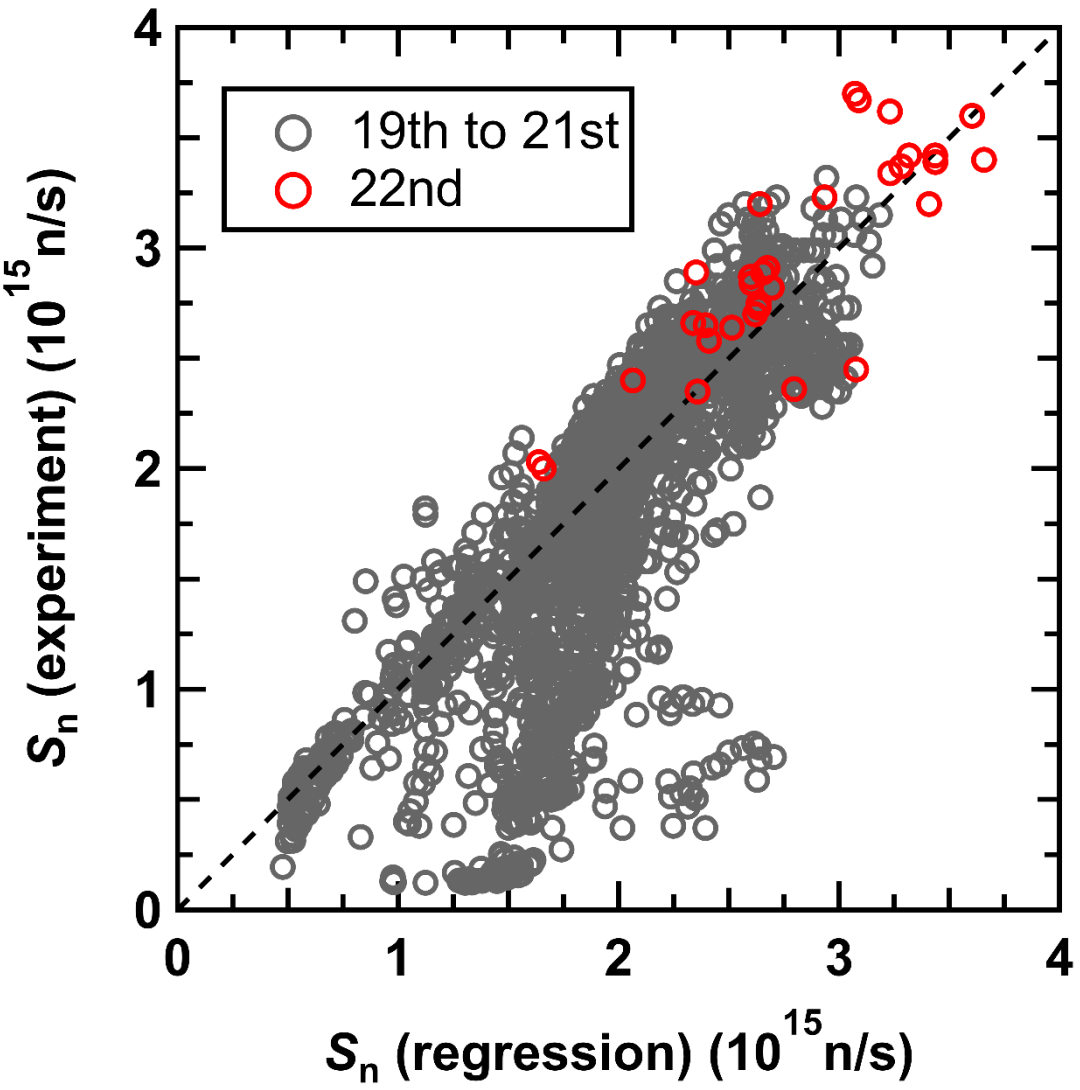

Figure 3. Comparison of experimentally obtained and calculated total neutron emission rate (S_n) in steady-state discharges. Although the newly obtained data in the 22nd LHD experimental campaign (red circle) gradually increased beyond the database established during the 19th and 21st campaigns (gray circle), the data achieved almost align with the regression guidelines, as shown with a dashed line.