Regression Approach for Acquiring a Quantitative Guidance toward Updating the Deuterium-Deuterium Fusion Neutron Emission Rate in the Large Helical Device

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(Received 15 October 2020 / Accepted 2 November 2020)

A regression approach has been adopted to acquire a quantitative guidance for updating the total neutron emission rate (S_n) in the Large Helical Device (LHD) with employing the externally controllable parameters such as heating power and plasma density. A deduced regression expression is worthwhile to understand for the contribution of an individual parameter during high S_n discharges, and then to be exploited in the experiment planning to update the record S_n value in LHD in the coming campaigns. It was found that S_n in high S_n discharges in LHD is expressed as $S_n = 10^{14.25} \times {n_{e\_avg}}^{0.52} \times {P_{N\text{-}NB}}^{0.69} \times {P_{P\text{-}NB}}^{0.37}$, where n_{e_avg}, $P_{N\text{-}NB}$, and $P_{P\text{-}NB}$ represent the line-averaged electron density [$10^{19}\,m^{-3}$] and the injection power of negative and positive ions based neutral beam injection [MW], respectively. This expression shows that, among three parameters, $P_{N\text{-}NB}$ is essential for achieving high S_n in this employed high S_n discharge database.

Keywords: Large Helical Device (LHD), total neuron emission rate, deuterium fusion reaction, regression approach

DOI: 10.1585/pfr.15.1202087

In deuterium-tritium (DT) fusion burning plasmas, the energy of DT fusion neutron absorbed by the blanket module is used for generating electrical power. Therefore, the fusion output from the plasma is the direct measure to show the accomplishment for realizing a fusion reactor. In a deuterium-deuterium (DD) experiment performed in large tokamaks e.g. TFTR, JT-60U, and JET, the total neutron emission rate (S_n) achieved approximately 5×10^{16} n/s which corresponds to the fusion output of approximately 60 kW [1–3]. In JET, empirical formulas of S_n were deduced for a prediction of the counting rate of the neutron camera [4]. The fusion performance of large-scale helical device has been indicated after starting deuterium operation in the Large Helical Device (LHD) in 2017. DD fusion performance, e.g. S_n of ~3.3×10^{15} n/s and ~3.0×10^{15} n/s were achieved in deuterium pellet and gas puff discharges, simultaneously using intensive neutral beam (NB) injections [5, 6]. In these high S_n discharges, simultaneous precise adjustments of experimental conditions such as a magnetic configuration, heating pattern, and density control are required, because in NB heated LHD plasmas, S_n depends on the plasma parameters such as plasma temperature and density as well as the injection energy and power of NBs. For updating S_n record in LHD, grasping the importance of each externally controllable parameter helps to decide the priority of adjustment of experimental conditions. In addition, this regression approach may contribute to controlling the steady state fusion reactor in the future. This paper represents the first result of an application of the regression approach for S_n in LHD. It is noted the here the same approach has been conducted to deduce regression expression of thermal diffusivities in high ion temperature plasmas in LHD with simple and plausible results [7].

We performed the experiment in NB heated deuterium plasmas using electron cyclotron heating (ECH), negative ion based neutral beam (N-NB) injections whose injection energy is up to 180 keV, and positive ion based neutral beam (P-NB) injections whose injection energy is up to 60/80 keV. The experimental data points sampled for this study satisfy the following general restrictions. (1). The preset magnetic axis position is 3.55 m, toroidal magnetic field strength is 2.89 T, the direction of the toroidal magnetic field is counterclockwise when viewed from above because this is the typical magnetic configuration of the high S_n discharge. (2). Line-averaged electron density (n_{e_avg}) is 1 - 3 × $10^{19}\,m^{-3}$. (3). The working gas is deuterium. (4). The working gas of N-NB and P-NB is deuterium and both N-NB and P-NB are injected without breakdown or sudden (or unintended) stop. (5). The intensity ratio of Dα to Hα is more than nine to one, which implies deuterium-dominant plasmas. (6). The timing is not an initiation phase of the discharge to avoid timing before NB absorption. Figure 1 shows the typical time evolution of NB heated deuterium plasma discharge. The region colored in yellow corresponds to the region of interest in

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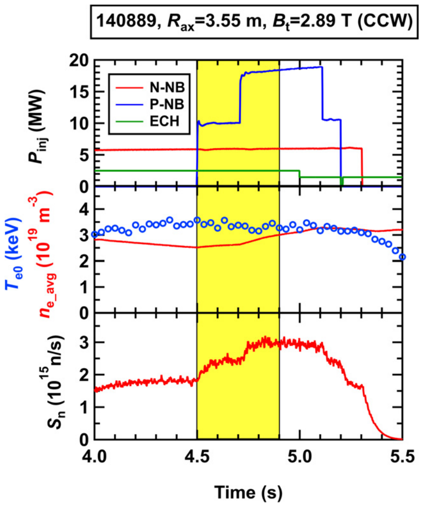

Fig. 1 Typical time evolution of deuterium plasma discharge. Yellow region fulfills the general restrictions in this analysis.

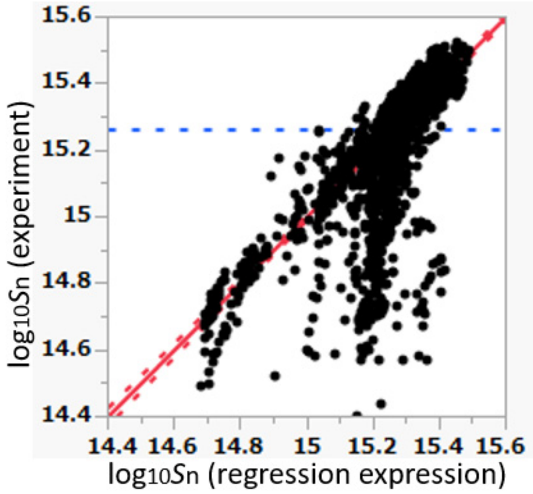

Fig. 2 Comparison of $\log_{10} S_n$ values between the experimental measurement (vertical axis) and ones based on the regression expression (horizontal axis).

this database. The injection power of N-NB ($P_{N\text{-}NB}$), P-NB ($P_{P\text{-}NB}$), and ECH (P_{ECH}) is ~6 MW, up to 18 MW, and 2.5 MW, respectively. The n_{e_avg} measured by the interferometer shows only a gradual change. The central electron temperature (T_{e0}) measured by the Thomson scattering diagnostics shows T_{e0} ~3 keV. The S_n measured by the neutron flux monitor [8] gradually increases, depending on the heating power. For each discharge, the database contains measured data value of up to 10 points. The number of available discharges is 443, with summing up the total of 1590 data points.

To identify the importance of parameters for S_n, only externally controllable parameters are used to conveniently plan the experimental scenario. Those parameters are n_{e_avg} [10^{19} m^{-3}], $P_{N\text{-}NB}$ [MW], $P_{P\text{-}NB}$ [MW], and P_{ECH}. During regression analysis, it was found that the importance of P_{ECH} is relatively low compared to the other parameters. The so-called log-linear multivariate regression is conducted to obtain the regression expression as

$$S_n = 10^{14.25} \times {n_{e\_avg}}^{0.52} \times {P_{N\text{-}NB}}^{0.69} \times {P_{P\text{-}NB}}^{0.37}.$$

The obtained expression shows that $P_{N\text{-}NB}$ contributes the most to an increase in S_n with the largest exponent. Note that ratio of S_n in experiment to regression prediction in highest S_n case is 1.13.

Figure 2 shows the comparison of $\log_{10} S_n$ values between the experimental measurement and ones based on the regression expression. Although the coefficient of determination, R^2, is as relatively high as 0.84, there are groups of data points (mostly data with S_n less than 10^{15}) deviating largely from the diagonal line shown in Fig. 2. In this study, we simply tried to express S_n using only a limited number of parameters which are externally controllable in terms of experimental planning. The regression can be improved if we employ the measurable plasma parameters such as temperature and density profiles such as described in Ref. [7]. This extended study will be performed in our future work. It is also noted that the regression expression is only valid in the range of an employed database. However, it would be worthwhile to extend the parameter regime of S_n gradually beyond it, that is, targeting record S_n value.

The regression analysis of S_n in deuterium LHD plasma was initiated to identify the importance of each externally controllable parameter for achieving higher S_n. The obtained expression shows that the injection power of N-NB is relatively important compared with the plasma density and injection power of P-NB in high S_n discharge database. The experiment targeting updating S_n record will be performed in coming LHD campaigns, based on this quantitative guidance deduced in this study.

This work is supported partly by the National Institute for Fusion Science Collaboration Research Program (KOAH037), LHD project budgets (ULHH034), and JSPS KAKENHI Grant No. JP 19K03797.

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