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Characterization of electron density based on operational parameters in JET H-mode plasmas with C and ILW

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1. Introduction

The plasma density is a key factor determining the fusion gain whereas little is known about how it is determined. In the JET ILW experiments, higher gas puffing rate is required to screen high-Z impurity influxes than the C wall. However, there is sometimes a difficulty in the preparation of the experiment where the electron density cannot easily be controlled. In other words, the electron density may be less affected by the external particle supplies of NB injection and gas puffing. Thus, this paper characterizes the electron density based on the operational parameters in JET H-mode plasmas with C and ILW using the multiple regression technique. It would be useful if the electron density could be predicted from the operational parameters before the experiment is performed. In addition, the electron density is generally used as an input parameter in confinement scaling laws in spite of the fact that the density is also obtained by a consequence of the particle transport. This uncertainty in the scaling laws may strongly affect the prediction of the energy confinement time. From these points of view, we examined if the electron density can be described with acceptable uncertainty by only the operational parameters.

2. Setup for the multiple regression analysis

The database has been constructed for H-mode plasmas with C and ILW, which consists of 2093 time windows for C and 3511 time windows for ILW. The data have been taken in stationary phases ($|\mathrm{d}W/\mathrm{d}t| < 2\mathrm{MW}$). Figure 1 shows the line-averaged electron density $\bar{n}_\mathrm{e}$ as a function of the plasma current I_p for C and ILW. There is a strong positive dependence of $\bar{n}_\mathrm{e}$ on I_p for both cases, whereas there is also a wide variation of $\bar{n}_\mathrm{e}$ even at a given I_p. In this analysis, five operational parameters of the plasma current I_p, toroidal field B_t, triangularity δ, NBI power P_NBI and gas puffing rate Φ_e were employed as shown in table 1.

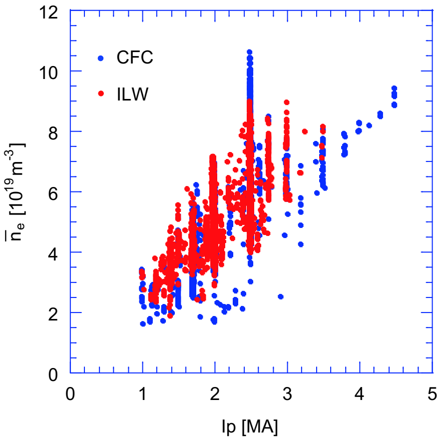

FIG. 1: The line-averaged electron density as a function of the plasma current for C and ILW.

Table 1: Ranges of the operational parameters employed in the multiple regression

Wall	$\bar{n}_\mathrm{e}$ [$10^{19}\mathrm{m}^{-3}$]	I_p [MA]	B_t [T]	δ	P_NBI [MW]	Φ_e [$10^{22}\mathrm{s}^{-1}$]
CFC	1.5 – 10.6	1.0 – 4.5	1.0 – 3.6	0.18 – 0.48	5.0 – 23.0	0.0 – 7.5
ILW	1.8 – 9.0	1.0 – 3.5	1.0 – 3.4	0.17 – 0.46	5.0 – 25.0	0.1 – 23.0

Considering that the electrons are provided by the ionization of neutral particles, there are three particle sources of recycling, gas puffing and NBI. In this analysis, P_{NBI} and Φ_{e} can be measures of particle sources. However, there is no certain measure of recycling because of the restriction where the regression is performed using only the operational parameters. Thus, it is also a question if $\bar{n}_{\mathrm{e}}$ can be described without a certain measure of recycling.

The multiple regression requires several preparation before it is performed to obtain a reliable result. First, the ranges of independent variables should be large enough to reduce the uncertainty. Among the employed variables, δ is only a variable which expresses the magnetic geometry. The other size relevant parameters like major radius and minor radius should be taken into account if the analysis extends over the multi-machine database. However, these variables are not flexibly changed within one device. Second, the experiments are conducted depending on the scientific interests and thus relatively concentrated at the experimental conditions of baseline and hybrid operations in JET. Therefore, an appropriate weight is allocated according to the data concentration so that the regression result would not be biased to the populated experiments. Third, the correlation coefficients should be as small as possible to avoid the potential multi-collinearity. In the database used in this study, only correlation coefficient between I_{p} and B_{t} of ~ 0.8, which arises mainly from the operational constraint of $q_{95} > 3$, is relatively large and may cause the multi-collinearity.

3. Regression analysis (I)

A log-linear regression model is employed which is a very common way to handle a non-linear relationship. The result of this regression model can be reformulated to a well-known power law expression.

$$\ln \bar{n}_{\mathrm{e}} = \ln C_0 + C_{\mathrm{IP}} \cdot \ln I_{\mathrm{p}} + C_{\mathrm{BT}} \cdot \ln B_{\mathrm{t}} + C_{\mathrm{DL}} \cdot \ln \delta + C_{\mathrm{NB}} \cdot \ln P_{\mathrm{NBI}} + C_{\mathrm{PF}} \cdot \ln \Phi_{\mathrm{e}} \quad (1)$$

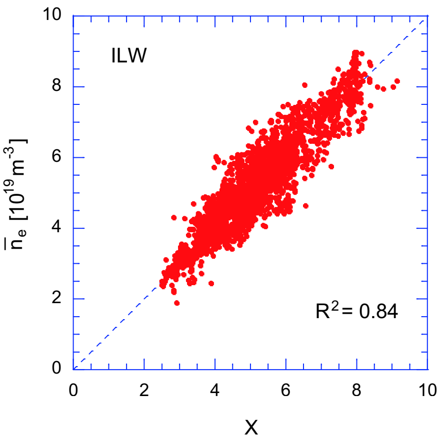

FIG. 2: The regression result for the electron density for ILW (I).

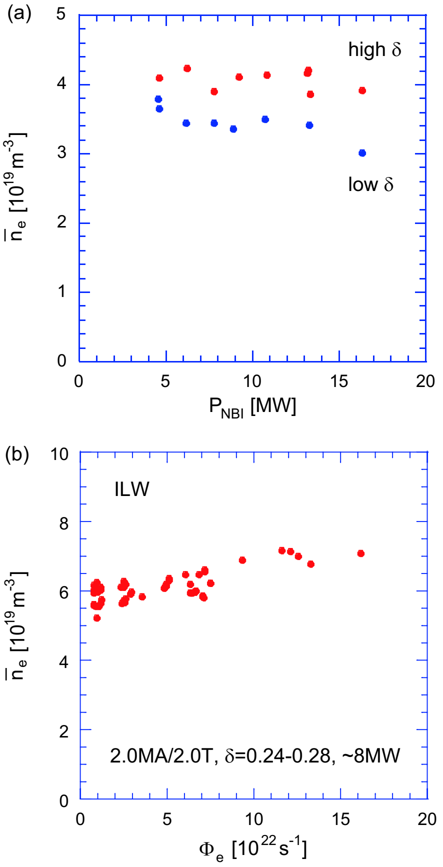

FIG. 3: Dependence of electron density on (a) P_{NBI} and (b) Φ_{e} for ILW.

Table 2: Coefficients of the operational parameters in the log-linear regression (I)

Wall	C_0	C_{IP}	C_{BT}	C_{DL}	C_{NB}	C_{PF}	R^2
CFC	5.87	1.24	-0.58	0.64	0.06	0.09	0.86
ILW	7.77	1.14	-0.38	0.56	-0.08	0.11	0.84

Table 2 shows the regression analysis result. Although there is ambiguity related to the collinearity between $I_{\rm p}$ and $B_{\rm t}$, the result shows a strong positive dependence on $I_{\rm p}$ and a negative dependence on $B_{\rm t}$ for both cases. Figure 2 shows the regression result for ILW. The electron density is well described by these operational parameters with uncertainty of $\pm 1 \times 10^{19}{\rm m}^{-3}$.

The exponent of $P_{\rm NBI}$ is negligibly small and there is weak positive dependence on $\Phi_{\rm e}$ for both cases of C and ILW. Figure 3(a) shows the $\bar{n}_{\rm e}$ as a function of $P_{\rm NBI}$ for the power scan experiments at low and high δ in ILW [1]. The electron densities remain roughly constant for both cases with the increase of $P_{\rm NBI}$. Figure 3(b) shows the $\bar{n}_{\rm e}$ as a function of $\Phi_{\rm e}$ whereas the other operational parameters are approximately fixed. There is a weak positive dependence of $\bar{n}_{\rm e}$ on $\Phi_{\rm e}$. The regression result is consistent with the experimental observations of these single parameter scan. These obervations indicate that increased particle sources of NBI and gas puffing enhance the particle diffusion so that the electron density remains approximately constant by $P_{\rm NBI}$ and is raised weakly by $\Phi_{\rm e}$.

4. Regression analysis (II)

One of the remedies to sort out the multi-collinearity between $I_{\rm p}$ and $B_{\rm t}$ is to examine the $B_{\rm t}$ dependence for an appropriate subset at fixed $I_{\rm p}$ and perform the regression assuming that the $B_{\rm t}$ dependence is applicable uniformly to the whole database. Figure 4 shows the $\bar{n}_{\rm e}$ as a function of $B_{\rm t}$ at 2MA for ILW. The electron density systematically decreases with increased $B_{\rm t}$. The regression analysis was done for subsets at fixed $I_{\rm p}$ for C and ILW. Then, a similar exponent for $B_{\rm t}$ was obtained which became -0.58 for C and -0.60 for ILW.

The second regression was performed based on the assumption where the $B_{\rm t}$ dependence obtained at fixed $I_{\rm p}$ is applicable to the whole database as shown in figure 5. The electron density is well described by these operational parameters with a better R^2 value than the previous result.

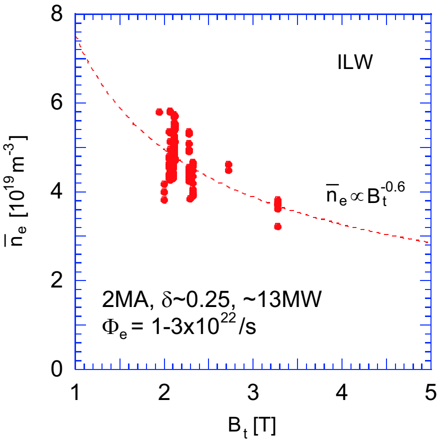

FIG. 4: Dependence of electron density on $B_{\rm t}$ at 2MA for ILW.

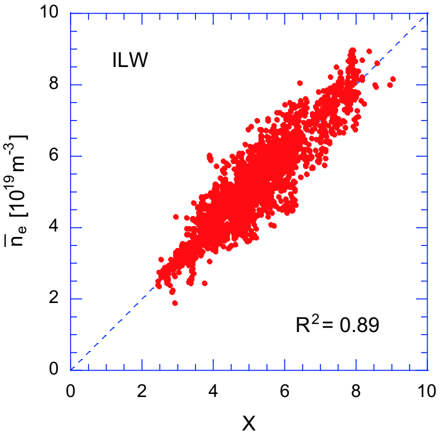

FIG. 5: The regression result for the electron density for ILW (II).

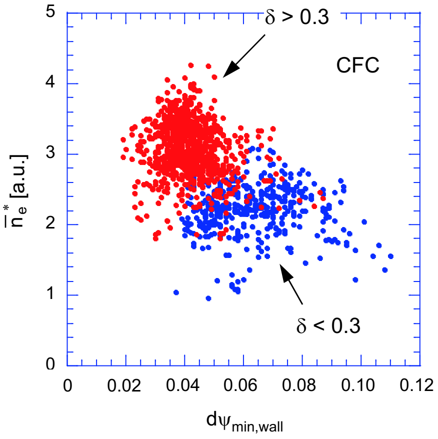

FIG. 6: The normalized $\bar{n}_{\rm e}$ as a function of the minimum difference of ψ between the LCFS and the first wall.

Table 3: Coefficients of the operational parameters in the log-linear regression (II)

Wall	C_0	$C_{\rm IP}$	$C_{\rm BT}$	$C_{\rm DL}$	$C_{\rm NB}$	$C_{\rm PF}$	R^2
CFC	7.00	1.33	-0.58	0.72	0.01	0.07	0.90
ILW	8.05	1.28	-0.60	0.54	-0.07	0.10	0.89

Table 3 shows the second regression analysis result. The exponents of all the variables but δ are nearly identical between C and ILW. The next question is why there is a different dependence of electron density on triangularity between C and ILW.

There are two possibilities which can explain the difference of the effect of triangularity on the electron density between C and ILW. Since the density is determined by the particle balance of the source and diffusion, one possibility is that the difference of the particle source appears through triangularity. The other is that the dependence of the particle confinement on triangularity is different between C and ILW.

In JET, when δ is raised, the LCFS gets close to the first wall at the upper left corner and the neutral pressure increases [2]. Figure 6 shows the electron density normalized to the regression result without the component of δ as a function of $\mathrm{d}\psi_{\mathrm{min,wall}}$ which is the minimum difference of the poloidal flux ψ between the LCFS and the first wall. The electron density is raised when the LCFS is close to the first wall. Besides, $\mathrm{d}\psi_{\mathrm{min,wall}}$ becomes smaller at higher δ configuration. In this analysis, the recycling effect is not explicitly included in the independent variables for the regression. In other words, the recycling effect may appear indirectly through δ. Among three particle sources of recycling, gas puffing and NBI, only the recycling is affected by the wall materials and the exponent of δ can be different between C and ILW.

The other possibility is a difference of particle confinement between C and ILW. In the C wall, there is a regime where a favorable energy and particle confinement is obtained at high triangularity with high gas flux close to the Greenwald density [3]. However, this regime has not been reproduced at high triangularity in the ILW but the confinement degrades simply with increased density. Thus, this systematic difference of confinement at high triangularity between C and ILW may correspond to the different exponents of triangularity in the multiple regression analysis.

5. Conclusions

We examined if the electron density could be described using the operational parameters in JET H-mode plasmas with C and ILW. It was found that the multiple regression using five operational parameters can describe the average electron density with uncertainty of $\pm 1 \times 10^{19}\mathrm{m}^{-3}$. The analysis result showed nearly no dependence of the electron density on P_{NBI} and a weak positive dependence on gas puffing rate for both C and ILW. The dependence on operational parameters for C was similar to ILW except triangularity. The difference of the exponent of triangularity between C and ILW may be caused by two possibilities of the effect of the recycling and particle confinement due to the difference of the wall materials.

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