EFFECTIVE CHARGE DEPENDENCE OF CONFINEMENT IMPROVEMENT FACTOR IN LHD

J. Miyazawa, H. Yamada, S. Morita, K. Tanaka, S. Sakakibara, M. Osakabe, Y. Xu, B.J. Peterson, S. Murakami, K. Narihara, H. Funaba, M. Goto, O. Kaneko, K. Kawahata, A. Komori, N. Ohyabu, and LHD experimental Group

National Institute for Fusion Science, Oroshi-cho 322-6, Toki, Gifu 509-5292, Japan

The Large Helical Device (LHD) experiment has demonstrated an energy confinement time exceeding the conventional energy confinement scaling such as the international stellarator scaling 95 (ISS95) with the improvement factor F_{ISS95} of 1.6±0.2 in an average [1], where $F_{\mathrm{ISS95}} = \tau_E^{\mathrm{EXP}}/\tau_E^{\mathrm{ISS95}}$, τ_E^{EXP} is the experimental energy confinement time, and τ_E^{ISS95} is that expected from the international stellerator scaling 95 (ISS95) as follows [2];

$$\tau_E^{\mathrm{ISS95}} = 0.079 a^{2.21} R^{0.65} P^{-0.59} n_e^{0.51} B^{0.83} \iota_{2/3}^{0.4}, \qquad (1)$$

with energy confinement time, τ_E, in s, absorbed heating power, P, in MW, line-averaged electron density, n_e, in 10^{19} m^{-3}, volume averaged magnetic field strength, B, in T, and $\iota_{2/3}$ is the normalized rotational transform ($\iota = \iota/(2\pi) = 1/q$; q is the safety factor) at the two-thirds radius. The scatter of F_{ISS95} suggests a hidden parameter dependence of confinement, although it still has the gyro-Bohm property. Considering simple two-component plasmas that contain electrons and ions of charge Z, the confinement property is a function of the ion gyro radius ρ_i, as long as the gyro-Bohm model is applicable to these plasmas. As for three-component plasmas that contain electrons and two kinds of ions, the effective charge, Z_{eff}, and an effective mass, A_{eff}, give the averaged ion gyro radius. At this point, usual scalings do not include Z_{eff} distributing from 1 to 6 in LHD plasmas. In this paper, we compare the experimental results of LHD and the gyro-Bohm model with/without considering Z_{eff} and A_{eff} to show the importance of them in the confinement scaling.

The picture of the gyro-Bohm model gives a thermal diffusivity χ in proportion to $\omega^* \rho_i^2$ (where ω^* is the drift frequency) [3]. Then the energy confinement time predicted by this model $\tau_E^{\mathrm{GB}} \sim a^2/\chi$ scales as below;

$$\tau_E^{\mathrm{GB}} = C_0\ a^{2.4} R^{0.6} B^{0.8} P^{-0.6} n_e^{0.6}. \qquad (2)$$

Note that the indices (of a, R, B, P, and n_e) in Eq. (2) are almost identical to that of ISS95 scaling in Eq. (1), except for the $\iota_{2/3}$ term. An adjustment factor C_0 is determined by the

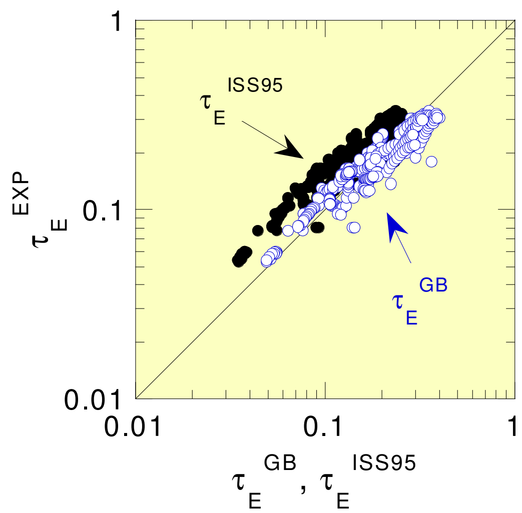

Fig. 1. Comparison of τ_E^{GB} and τ_E^{EXP} (blue open circles), τ_E^{ISS95} and τ_E^{EXP} (black closed circles).

experimental data to give the ratio $F_{GB} = \tau_E^{EXP}/\tau_E^{GB} = 1$. Here, $C_0 = 0.105$ and $F_{GB} = 1.00\pm0.16$ are obtained. Comparison of τ_E^{EXP} with τ_E^{GB} (or, τ_E^{ISS95}) is depicted in Fig. 1. The scatter of F_{GB} is almost the same as that of F_{ISS95} (= 1.44±0.21, in this data set). The data set used here consists of 359 data points extracted from 32 shots of hydrogen or helium gas-puff discharges heated by the neutral beam (NB) injection only. The magnetic configuration is fixed to R_{ax} = 3.6 m (R_{ax} is the vacuum magnetic axis), and in consequence, R ~ 3.69 m, a ~ 0.63 m, and $\iota_{2/3}$ ~ 0.64 are almost unchanged. Each data point is extracted according to some criteria, *i.e.* the ratio of $|dW_p/dt|$ to P (= P_{NB}), where W_p is the plasma stored energy and P_{NB} is the NB heating power, is lower than 3% and therefore negligible, the changing rate of electron density ($n_e/(dn_e/dt)$) is less than 1 s, and $n_e > 1\times10^{19}$ m^{-3}. Meanwhile, the gyro-Bohm model in Eq. (2) is incomplete since it does not include the terms of Z_{eff} and A_{eff}. Another energy confinement time τ_E^{GBZ} predicted by the gyro-Bohm model consisting of Z_{eff} dependence is given as below;

$$\tau_E^{GBZ} \propto a^{2.4}R^{0.6}B^{0.8}P^{-0.6}n_e^{0.6}A^{-0.2}(Z^4+3Z^3+3Z^2+Z)^{0.2},$$

$$= F_Z\tau_E^{GB}, \qquad (3)$$

where $F_Z = C_1A^{-0.2}(Z^4+3Z^3+3Z^2+Z)^{0.2}$ and if Eq. (2) is valid in pure hydrogen plasmas, $C_1 = 8^{-0.2}$. Non-linear term of Z comes from a relation $P\tau_E^{GBZ} \propto (1 + 1/Z)n_eTa^2R$ used to obtain Eq. (3). If this model well describes LHD plasmas ($\tau_E^{EXP} = \tau_E^{GBZ}$), F_{GB} will be equivalent to F_Z and have a strong dependence on Z.

A correlation study of F_{GB} is carried out with various plasma parameters to find out the hidden parameter dependence. The typical ten global parameters are examined, *i.e.* B, P_{NB}, Z_{eff}, n_e and its peaking factor n_{e0}/n_e (n_{e0} is the electron density at the plasma center), the electron temperature T_{e0} (at the plasma center) and T_{e_ped} (at the pedestal around $\rho = r/a$ ~ 0.9), the peaking factor of the electron temperature T_{e0}/T_{e_ped}, the radiation loss P_{rad} and its ratio to the heating power P_{rad}/P_{NB}. Table 1 is a list of correlation coefficients R_c obtained in the full data set consisting of 359 data points and the partial data set consisting of 86 data points (see below about the partial data set). The largest R_c of 0.84 is obtained between Z_{eff} and F_{GB}, as depicted in Fig. 2(a). The second (third) candidate is T_{e0} (n_e) that has R_c of 0.77 (0.56) (see Figs. 2(b) and (c)). Other parameters have low R_c less than 0.5, and therefore these are less influential. One should be careful to note that T_{e0} might depend on n_e when the heating power is fixed, and Z_{eff} is also

Table 1. Correlation coefficients R_c between ten global plasma parameters and F_{GB} in the full and the partial data sets.

Parameter	R_c (full)	R_c (partial)
Z_{eff}	0.84	0.60
T_{e0}	0.77	0.12
n_e	0.56	0.22
T_{e_ped}	0.43	0.22
T_{e0}/T_{e_ped}	0.40	0.15
B	0.30	0.31
$P_{NB}-dW_p/dt$	0.14	0.14
$P_{rad}/(P_{NB}-dW_p/dt)$	0.11	0.04
P_{rad}	0.08	0.04
n_{e0}/n_e	0.01	0.01

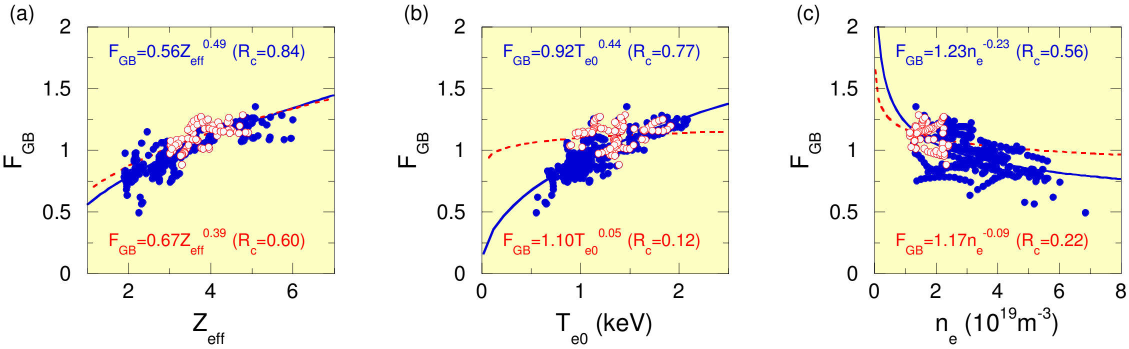

Fig. 2. Linear correlations between (a) Z_{eff} and F_{GB}, (b) T_{e0} and F_{GB}, (c) n_e and F_{GB}. Closed and open circles denote the full data set of 359 points and the partial data set of 86 points, respectively. The correlation coefficient R_c in the full (partial) data set is indicated on the top (bottom) of each figure together with the best-fit curve of solid (broken) line.

dependent on n_e if the impurity influx is constant. In this data set, Z_{eff} weakly correlates with n_e as shown in Fig. 3(a), where Z_{eff} tends to become smaller in the high-density region. This suggests that the influx of impurities is limited and the purity increases in the high-density range where plenty of fuelling gas is puffed. Nevertheless, R_c between n_e and Z_{eff} (or, T_{e0}) is as small as 0.45 (0.31), and therefore negligible. On the other hand, the correlation between Z_{eff} and T_{e0} is not negligible (R_c = 0.72, Fig. 3(c)). It is possible to eliminate this dependence by limiting the boundary of the data set as $1 < n_e$ ($10^{19}m^{-3}$) < 2.5, $3 < Z_{eff} < 5$, and P_{NB} (MW) < 2. Open circles in Figs. 2 and 3 denote the partial data set obtained after this limitation. Then Z_{eff} and T_{e0} are completely decorrelated (R_c = 0.11). Returning to Fig. 2(b), it can be seen that the correlation between T_{e0} and F_{GB} disappears (R_c = 0.12) in the partial data set, while the strong correlation of R_c = 0.60 still exists between Z_{eff} and F_{GB}. Correlations between F_{GB} and other eight plasma parameters become weaker after the limitation and the correlation coefficients of them are less than 0.31 (see Table 1).

According to these results, Z_{eff} has the largest influence on F_{GB} and therefore the regression analysis considering Z_{eff} together with P, n_e, B will give a strong dependence of the

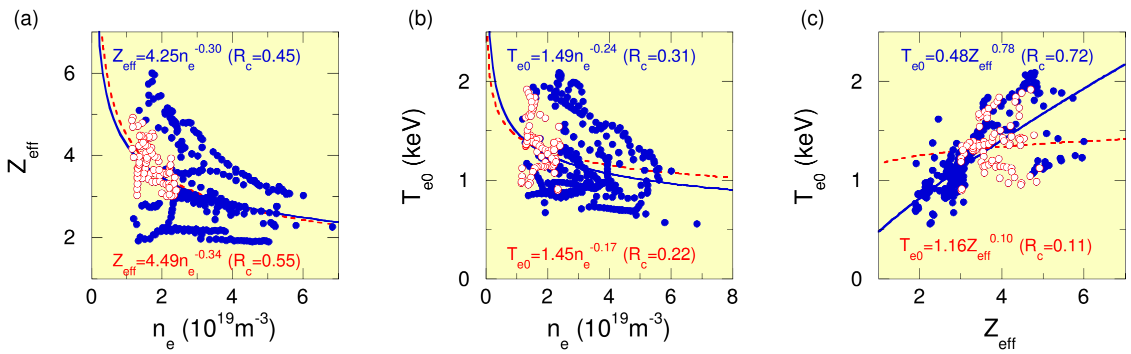

Fig. 3. Linear correlations between (a) n_e and Z_{eff}, (b) n_e and T_{e0}, (c) Z_{eff} and T_{e0}. Closed and open circles denote the full data set of 359 points and the partial data set of 86 points, respectively. The correlation coefficient R_c in the full (partial) data set is indicated on the top (bottom) of each figure.

data set on Z_{eff}. In our data set, all correlations between any two of P, n_e, B and Z_{eff} are less than 0.5 and therefore these parameters are independent. The result of regression analysis is;

$$\tau_E^{FIT} = 0.041 P^{-0.70\pm0.01} n_e^{0.54\pm0.02} B^{0.91\pm0.02} Z_{eff}^{0.55\pm0.02}. \tag{4}$$

A strong dependence on Z_{eff} appears as expected and all indices are almost the same as Eq. (3). Therefore, τ_E^{GBZ} can be a nice model to describe τ_E^{EXP}, and F_{GB} will have the same dependence on Z_{eff} and A_{eff} as F_Z. To examine this, A_{eff} is uniquely determined from Z_{eff} assuming three-component plasmas with the majority ions of A = 2.5 and Z = 1.67 (since the data set consists of hydrogen and helium discharges), and impurity ions of A = 15 and Z = 7. Exponential fit of F_{GB} with a parameter $(Z_{eff}^4+3Z_{eff}^3+3Z_{eff}^2+Z_{eff})/A_{eff}$ then gives

$$F_{GB} = 0.42((Z_{eff}^4+3Z_{eff}^3+3Z_{eff}^2+Z_{eff})/A_{eff})^{0.20\pm0.01}, \tag{5}$$

with a large correlation coefficient of 0.83. The exponent is exactly equal to that of F_Z, assuring the validity of Eq. (3). Therefore, a better prediction of τ_E^{EXP} can be given by $\tau_E^{GBZ} = F_Z \tau_E^{GB}$, which consists of the Z_{eff} dependence. Substituting Eq. (5) for F_Z in Eq. (3) (C_1 = 0.42), we finally obtain

$$\tau_E^{GBZ} = 0.044 a^{2.4} R^{0.6} B^{0.8} P^{-0.6} n_e^{0.6} A^{-0.2} (Z_{eff}^4+3Z_{eff}^3+3Z_{eff}^2+Z_{eff})^{0.2}. \tag{6}$$

In Fig. 5, compared are the distributions of $\tau_E^{EXP}/\tau_E^{GBZ}$ (= 1.03±0.09), τ_E^{EXP}/τ_E^{GB} (= F_{GB} = 1.00±0.16) and $\tau_E^{EXP}/\tau_E^{ISS95}$ (= F_{ISS95} = 1.44±0.21). The scatter of the prediction has been almost halved by this revision. The standard deviation of $\tau_E^{EXP}/\tau_E^{GBZ}$ is 8.8% and much smaller than that of F_{GB} (15.9%) or F_{ISS95} (14.4%). These results indicate the importance of Z_{eff} on the confinement scaling.

In conclusion, it is possible to increase the accuracy of an energy confinement scaling of high-temperature plasmas, which can be well described by the gyro-Bohm model, after introducing the Z_{eff} terms. This comes from a simple assumption that the energy confinement is a function of the averaged ion gyro radius determined by Z_{eff}.

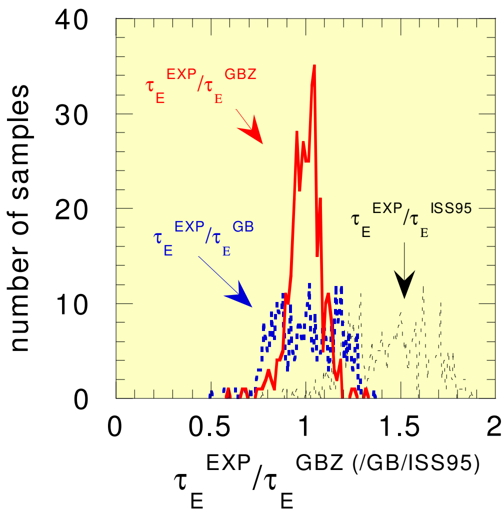

Fig. 4. Distributions of $\tau_E^{EXP}/\tau_E^{GBZ}$ (red solid line), τ_E^{EXP}/τ_E^{GB} (blue broken line), and $\tau_E^{EXP}/\tau_E^{ISS95}$ (black broken line).

References

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