§6. Effective Charge Dependence of Confinement Improvement Factor in LHD

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

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

However, the scattering of the improvement factor that ranges from 0.9 to 2.0 suggests a hidden parameter dependence of the confinement property, although it still shows the gyro-Bohm nature. Regarding three-component plasmas that contain electrons and two kinds of ions, the effective charge Z_{eff} determines the averaged ion gyro radius. At this point, usual scalings do not include Z_{eff} distributing from 2 to 6 in LHD plasmas. In the gyro-Bohm model, the turbulence that drives the anomalous transport has a scale length of the order of ion gyro radius ρ_i with a decorrelation time of the ion diamagnetic drift time ω^{*-1} [3]. The thermal diffusivity χ in this model scales as $\chi \propto \omega^* \rho_i^2$ and then the confinement time predicted by this model $\tau_E^{GB} \sim a^2/\chi$ scales as below;

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

An adjustment factor C_0 is determined by the experimental data to give the ratio $F_{GB} = \tau_E^{EXP}/\tau_E^{GB} = 1$. In the dataset used here, $C_0 = 0.105$ and $F_{GB} = 1.00\pm0.16$ are obtained. The scatter of F_{GB} is almost the same as that of F_{ISS95} (= 1.44±0.21, in this dataset). The dataset 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, $R \sim 3.69$ m, $a \sim 0.63$ m, and $\iota_{2/3} \sim 0.64$ are almost unchanged. Each data points are extracted according to some criteria, *i.e.* the ratio of $|dW_p/dt|$ to P (where W_p is a plasma stored energy) 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 including Z_{eff} terms is given as

$$\tau_E^{GBZ} = C_1 a^{2.4} R^{0.6} B^{0.8} P^{-0.6} n_e^{0.6} A^{-0.2} (Z^4+3Z^3+3Z^2+Z)^{0.2}. \quad (3)$$

The relation $P\tau_E^{GBZ} \propto (1 + 1/Z) n_e T a^2 R$ is used to obtain eq. (3). Regression analysis is carried out assuming the mass of 2.5 (15) and the charge of 1.67 (7) for the majority (impurity) ions, and the result is given as below;

$$\tau_E^{FIT} = 0.045 \times P^{-0.70\pm0.01} n_e^{0.53\pm0.02} B^{0.91\pm0.02} Z_{eff}^{0.74\pm0.07} A_{eff}^{-0.23\pm0.07}$$

The indices of Z_{eff} and A_{eff} are almost identical to the gyro-Bohm scaling, together with that of P, n_e, and B. This agreement shows the propriety of eq. (3) as the model of LHD plasmas. Determining the adjustment factor C_1 to give $\tau_E^{EXP}/\tau_E^{GBZ} = 1$, we obtain

$$\tau_E^{GBZ} = 0.044 \times a^{2.4} R^{0.6} B^{0.8} P^{-0.6} n_e^{0.6} A^{-0.2} (Z^4 + 3Z^3 + 3Z^2 + Z)^{0.2}. \quad (4)$$

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 scalings.

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}.

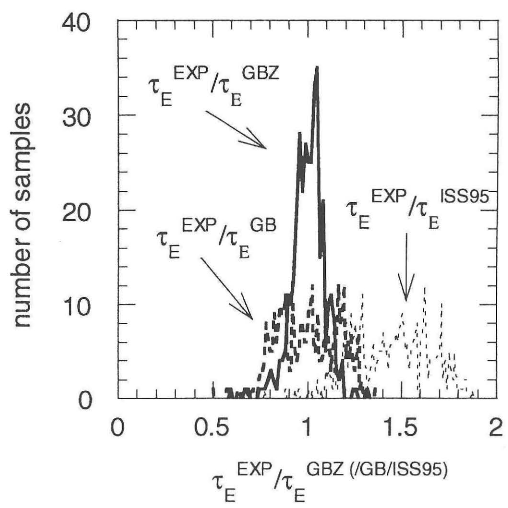

Fig. 1. Distributions of $\tau_E^{EXP}/\tau_E^{GBZ}$ (thick solid line, $\tau_E^{EXP}/\tau_E^{GB} = F_{GB}$ (thick broken line), and $\tau_E^{EXP}/\tau_E^{ISS95} = F_{ISS95}$ (thin dotted line).

References

1) Stroth, U. et al. : Nucl. Fusion **36**, 1063 (1996).
2) Yamada, H. et al. : Nucl. Fusion (in press).
3) Cordey, J. G. *et al.* : Nucl. Fusion **39**, 301 (1999).