Global gyrokinetic simulations of isotope effects for future tokamak plasma core and pedestal

Lei Qi[1]+, T. S. Hahm[1,2], Jae-Min Kwon[1], M. Leconte [1]
[1]Korea Institute of Fusion Energy (KFE), Daejeon, Korea
[2]Seoul National University (SNU), Seoul, Korea
+Corresponding Author: *qileister@kfe.re.kr*

The value of gyrokinetic simulation and modelling of tokamaks lies in providing insights for the development of future laboratory machines and reactors, such as ITER, DEMO and fusion plants. Precise predictions for future tokamaks can greatly aid in the design of reactors and their associated heating systems. Gyrokinetic simulations already indicate that in future, larger tokamaks, the anomalous transport level will follow a gyro-Bohm scaling, in contrast to a Bohm scaling observed in smaller, past and present-day tokamaks[1,2]. A subsequent study[3] further elaborates this system size dependence is directly influenced by the size of turbulence region rather than the tokamak's minor radius. Meanwhile, a flux-driven full-f simulation[4] has not observed a transition to gyro-Bohm scaling from a system size scan.

In magnetically confined fusion plasmas, the most efficient way to achieve burning plasmas in future tokamaks and fusion plants is to utilize hydrogen isotopes deuterium (D) and tritium (T), leveraging their favorable fusion cross sections. Experiments on past and present-day tokamaks have demonstrated a favorable isotopic dependence of the energy confinement across different operational regimes, yielding an empirical scaling $\tau_E \propto M_i^{\sigma}$. The exponent σ is positive and typically ranges from 0.2 to 0.5; τ_E represents the energy confinement time, and M_i denotes the isotope mass ratio to hydrogen. A recent update of H-mode data from JET-ILW and ASDEX-Upgrade (AUG) indicates the exponent σ to be in the range of 0.09-0.47[5]. The favorable isotopic dependence of energy confinement has also been observed in an alternative magnetic configuration, stellarators[6,7,8].

Predictions for future tokamaks and fusion plants heavily rely on empirical scaling laws derived from past tokamaks, such as L-mode confinement scaling ITER89-P[9] and the H-mode confinement scaling ITER-IPB(y)[10], along with ITPA activities to update databases from current tokamaks. ITER89-P and ITER-IPB(y) indicate σ =0.5 and σ =0.2, respectively. However, extrapolations to future tokamaks and fusion plants based on these scaling laws may encounter unexpected changes in trend, induced by substantial dimensional disparities between current (and past) tokamaks and future ones (e.g., the Bohm to gyro-Bohm transition). There are evident system size gaps in the dimensionless parameter $\rho^{*-1} \equiv a/\rho_i$, which is typically on the order of $\rho^{*-1} \sim 10^3$ for future tokamaks and fusion plants, compared to $\rho^{*-1} \sim 10^2$ for past and present-day tokamaks, which is much smaller. Therefore, dedicated investigations into the isotopic dependence of energy confinement from current to future tokamaks are highly desirable.

Recently, a dedicated gyrokinetic simulation has quantitatively reproduced the empirical scaling law for the isotopic dependence of energy confinement as derived from past and present-day tokamaks[11]. A novel mechanism has been identified, in which the turbulence radial correlation length, $l_{cr} \propto M_i^{0.11}$, significantly deviates from gyro-Bohm scaling. This deviation has been demonstrated to be crucial for understanding isotope effects, prompting further investigation into the properties of turbulence radial correlation and their impact on energy confinement from past and current to future tokamaks. The quantitative agreement between the gyrokinetic simulations and experimental results from previous and present-day tokamaks provides a solid basis for exploring isotope effects in forthcoming tokamaks. In this work, we present a reversal in the isotopic dependence of energy confinement in the tokamak plasma core from past to future tokamaks, as shown in the figure. The favorable isotope effects on the energy confinement observed in past and present-day tokamaks may diminish or reverse in future tokamaks with significantly larger ρ^{*-1}. This finding offers critical insights for the design of future tokamaks, such as ITER, DEMO and fusion plants, particularly those with larger sizes or stronger magnetic fields. The primary mechanism driving this reversal is the isotope mass dependence of the turbulence radial correlation length, which is significantly weaker than Bohm scaling at low ρ^{*-1} and closer to gyro-Bohm scaling at high ρ^{*-1}. In addition, our work also implies the study of impurity transport and energetic particle transport should consider the system size effects.

On the other hand, future tokamaks, such as ITER, DEMO, and reactor-scale devices, will likely operate in H-mode. Predicting the role of isotope mass in energy confinement for these H-mode scenarios remains a critical challenge. While the plasma core contains most of the plasma energy, the pedestal, characterized by a sharp transport barrier, plays a crucial role in overall confinement. Understanding isotope effects in the pedestal region is a critical and challenging issue. In this work, we will also extend our study from the core, and report on the trend of isotopic dependence in H-mode pedestal confinement as system size increases to that of future tokamaks. We also identify the underlying physical mechanisms and compare them with those governing isotope effects in the plasma core.

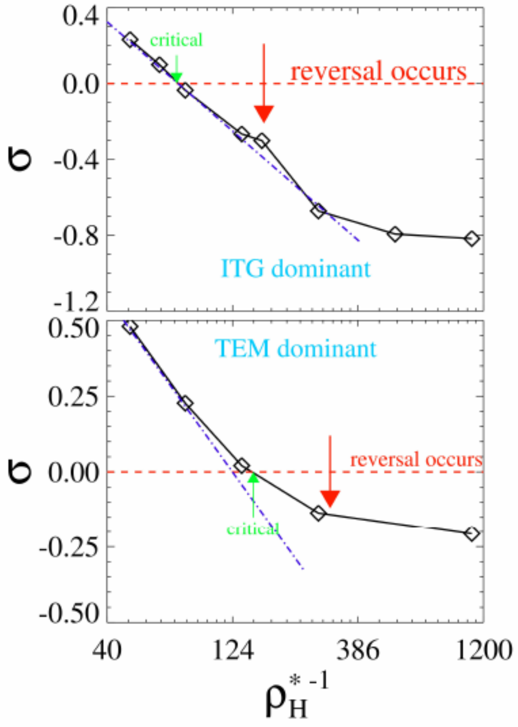

FIG. 2. Exponent σ is plotted with varying ρ_H^{*-1} for both ITG (top) and TEM (bottom) turbulence. Green arrows indicate the critical ρ_H^{*-1}, where σ crosses 0 and reverses its sign. The reversal is shown by red arrows. Blue dash-dot lines are by the formula $\sigma = -1.17 \log_{10} \rho_H^{*-1} + \text{const.}$.

[1] Z. Lin, S. Ethier, T. S. Hahm and W. M. Tang, Phys. Rev. Lett. **88**, 195004 (2002).
[2] Y. Xiao and Z. Lin, Phys. Rev. Lett. **103**, 085004 (2009).
[3] B. F. McMillan, X. Lapillonne, S. Brunner, L. Villard, S. Jolliet, A. Bottino, T. Gorler, and F. Jenko, Phys. Rev. Lett. **105**, 155001 (2010).
[4] Y. Idomura and M. Nakata, Phys. Plasmas **21**, 020706 (2014).
[5] G. Verdoolaege, et al., Nucl. Fusion **61**, 076006 (2021).
[6] H. Yamada, et al., Phys. Rev. Lett. **123**, 185001 (2019).
[7] K. Nagaoka, et al., Nucl. Fusion **59**, 106002 (2019).
[8] T. Kinoshita, et al., Phys. Rev. Lett. **123**, 235101 (2024).
[9] P. N. Yushmanov, et al., Nucl. Fusion **30**, 1999 (1990).
[10] M. Wakatani, et al., Nucl. Fusion **39**, 2175 (1999).
[11] L. Qi, J. M. Kwon, T. S. Hahm, et al., Phys. Rev. Research **6**, L012004 (2024).