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

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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. 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[1,2,3]. Meanwhile, a flux-driven full-f simulation[4] has not observed a transition to gyro-Bohm scaling from a system size scan due to prevalent large scale non-local avalanches.

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 have demonstrated a favorable isotopic dependence of the energy confinement $\tau_E \propto M_i^{\sigma}$. The exponent σ typically ranges from 0.2 to 0.5; 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 stellarators[6,7,8].

Predictions for future tokamaks heavily rely on empirical scaling laws, such as L-mode confinement scaling ITER89-P[9] and the H-mode confinement scaling ITER-IPB(y)[10], along with ITPA activities. ITER89-P and ITER-IPB(y) indicate σ =0.5 and σ =0.2, respectively. However, extrapolations to future tokamaks may encounter unexpected changes in trend, induced by substantial dimensional disparities between current (and past) tokamaks and future ones. 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. 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 [11]. A crucial 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 quantitative agreement 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 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 also studied.

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.

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Figure 1

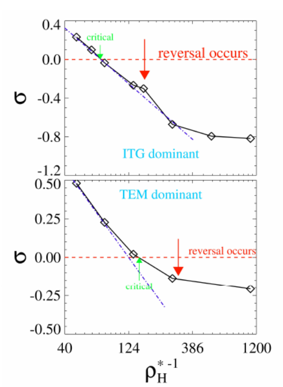

FIG. 2. Exponent σ is plotted with varying ρ_H^{*-1} for both ITG (top) and TEM (bottom) turbulence. Green arrows indicate the critical ρ_H^{*-1}, where σ crosses 0 and reverses its sign. The reversal is shown by red arrows. Blue dash-dot lines are by the formula $\sigma = -1.17 \log_{10} \rho_H^{*-1}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