7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Role of isotopes in microturbulence from linear to saturated Ohmic confinement regimes

Lei Qi, Jae-Min Kwon, T. S. Hahm, M. Leconte, Sumin Yi, Y. W. Cho and Janghoon Seo
Korea Institute of Fusion Energy, Daejeon 169-148, South Korea
e-mail (speaker): qileister@kfe.re.kr

Deuterium (D) and tritium (T), pivotal to fusion energy, serve as the fuel for power generation in fusion plants, making their reactor-level operation a crucial objective for ITER[1]. Various tokamak experiments have shown that isotopes enhance energy confinement, characterized by a scaling $\tau_E \propto M_i^\sigma$, where τ_E denotes energy confinement time, M_i represents the isotope mass ratio to hydrogen, and σ varies approximately between 0.2 and 0.5[2,3,4] in nearly all tokamak operation regimes. Notably, isotopic dependence in Ohmic plasmas on ASDEX displayed $\sigma = 0.31$ in low density linear Ohmic confinement (LOC) regime and $\sigma = 0.5$ in high density saturated Ohmic confinement (SOC) regime[2]. The empirical scaling laws for isotope effects have produced $\sigma = 0.5$ as per the ITER L-mode power scaling ITER89-P[5] and $\sigma = 0.2$ according to the ITER H-mode confinement scaling ITER-IPB(y)[3]. Further, recent experiments have shed light on the influence of isotopes on the L-H power threshold in DIII-D[6], as well as on the pedestal height in JET with an ITER-like wall[7] and ASDEX Upgrade[8]. Given these findings, it is pivotal to unravel the effects of isotopes in less complex plasma states like Ohmic and L-mode.

The first principle gyrokinetic numerical experiments investigating the isotopic dependence of energy confinement achieve a quantitative agreement with experimental empirical scalings, particularly in Ohmic and L-mode tokamak plasmas. Figure 1 compares the numerical results (Fig.1a) with the experimental measurements (Fig.1b) in ASDEX, indicating an excellent agreement in the trend. In addition, the scaling factor σ from the numerical experiments shows a quantitative consensus with the empirical scalings from ASDEX[2], ITER89-P[5] for L-mode and ITER-IPB(y)[3] for H-mode, as illustrated in Table I.

Mitigation of turbulence radial electric field intensity $|\delta E_r|^2$ and associated poloidal $\boldsymbol{\delta E_r} \times \boldsymbol{B}$ fluctuating velocity with the radial correlation length $l_{cr} \propto M_i^{0.11}$ strongly deviating from the gyro-Bohm scaling is identified as the principal mechanism behind the isotope effects. Three primary contributors are classified, the deviation from gyro-Bohm scaling, zonal flow and trapped electron turbulence stabilization. Contributions from these three mechanisms are also quantified as shown in Figure 2. Zonal flow enhances isotope effects primarily through reinforcing the inverse dependence of turbulence decorrelation rate on isotope mass with $\omega_c \propto M_i^{-0.76}$, which markedly differs from the characteristic linear frequency. The findings offer new insights into isotope effects, providing critical implications for energy confinement optimization in tokamak plasmas.

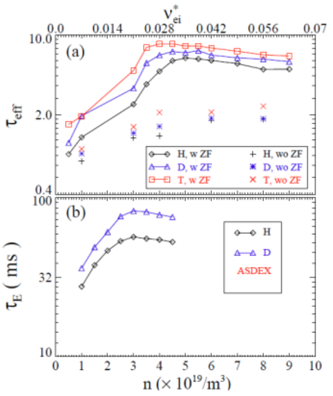


Figure 1: (a) Effective thermal energy confinement time τ_{eff} is depicted as a function of density n for cases with zonal flows (w ZF) and without zonal flows (wo ZF), and for H, D and T. (b) Energy confinement time as a function of density adapted from Fig.1b in Ref: M. Bessenrodt-Weberpals, F. Wagner, ASDEX TEAM, Nuclear Fusion, Vol. 33, No. 8 (1993).

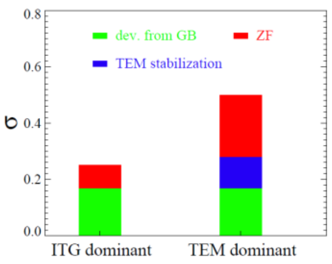
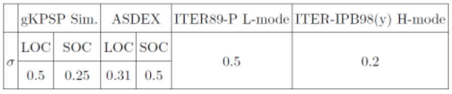


Figure 2: Contributions to the scaling factor σ in the isotopic dependence of energy confinement scaling $\tau_{eff} \propto M_i^\sigma$ from the three participators, deviation from gyro-Bohm scaling (green), TEM stabilization (blue) and zonal flow (red) in both ITG dominant and TEM dominant regimes are presented.

TABLE I: Predicted isotope scaling exponent σ of the energy confinement: $\tau \propto M_i^\sigma$ in comparison with empirical scalings.



	gKPSP Sim.		ASDEX		ITER89-P L-mode	ITER-IPB98(y) H-mode
σ	LOC	SOC	LOC	SOC	0.5	0.2
	0.5	0.25	0.31	0.5		

References

[1] B. Bigot, Nucl. Fusion **59**, 112001 (2019)
[2] M. Bessenrodt-Weberpals et al., Nucl. Fusion **33**, 1205 (1993)
[3] ITER Physics Expert Group on Confinement and Transport, Nucl. Fusion **39**, 2175 (1999)
[4] K. Ida, Rev. Mod. Plasma Phys. **7**, 23 (2023)
[5] P. N. Yushmanov et al., Nucl. Fusion **30**, 1999 (1990)
[6] Z. Yan et al., Nucl. Fusion 57, 126015 (2017)
[7] C. F. Maggi et al., Nucl. Fusion 59, 076028 (2019)
[8] P. A. Schneider et al., Plasma Phys. Control. Fusion 63, 064006 (2021)