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Can turbulent transport in optimized stellarators be lower than tokamaks?

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Stellarators with 3-dimensional (3D) magnetic configurations are an attractive fusion reactor concept thanks to their steady state operation and reduced risk of disruptions since no plasma current drive is needed. With recent progress on optimized stellarator designs leading to drastically reduced neoclassical transport and energetic particle orbit loss, there is a pressing need to evaluate the turbulent transport in these stellarators and to incorporate optimization of turbulent transport in the reactor design. To be a competitive reactor candidate, the optimized stellarators need to demonstrate a turbulent transport level similar to or lower than an axisymmetric tokamak.

In this work, global gyrokinetic GTC [1] simulations find that turbulent transport driven by the electrostatic ion temperature gradient (ITG) instability in the model equilibria of the QI [2] and quasi-helical symmetric (QH) [3] stellarators is at a level similar to that in an ITER tokamak scenario [4], despite a much larger linear growth rate in the stellarators. The underlying physics is found to be the reduction of turbulent transport by zonal flows, which have much higher linear residual levels and lower nonlinear frequencies in the QI and QH stellarators than the tokamak or the quasi-axisymmetric (QA) [3,5] stellarator. These results demonstrate the potential of the optimized stellarators as a promising reactor candidate and suggest a new research direction by optimizing zonal flow dynamics for the turbulence self-regulation to improve plasma confinement in the design of stellarator reactors.

Comparisons of turbulent transport levels— We first performed simulations with temperature gradient of $a/L_T = 1.4$. The most striking result shown in FIG.1 (a) is that the heat conductivities χ_i of the QH and QI are similar to the tokamak in the quasi-steady state, despite the much smaller linear

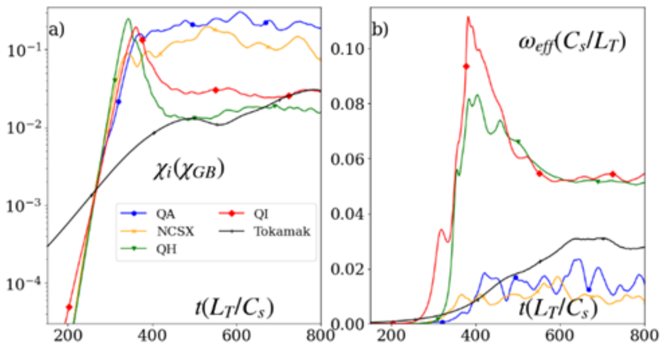

FIG. 1: *Time history of heat conductivity χ_i (panel a) defined as $\chi_i \equiv QL_T/nT$ and is normalized to gyroBohm unit $\chi_{GB} \equiv \rho_s^2 C_s/L_T$ and zonal flow effective shearing rate* [6] *ω_{eff} (panel b) defined as $\omega_{eff} = \omega_E[(1+3F)^2 + 4F^3]^{1/4}/[(1+F)\sqrt{1+4F}]$ with $F \equiv \omega_{zf}^2/\Delta\omega_T^2$. ω_E is the shearing rate. ω_{zf} is the frequency of the zonal flow and $\Delta\omega_T$ is the decorrelation rate of the ambient turbulence.*

growth rate γ in the tokamak. On the other hand, the χ_i of the QA (and NCSX) in the quasi-steady state are much higher than the QH and QI even though the linear growth rates and initial saturation levels are similar in all stellarators. In the quasi-steady state turbulence, the ω_{Eff} of the QH and QI are much larger than the QA and tokamak, as shown in FIG. 1 (b). Consequently, the χ_i of the QH and QI is much smaller than QA and tokamak. These differences in transport and zonal flows are consistent and indicate different zonal flow dynamics in different devices

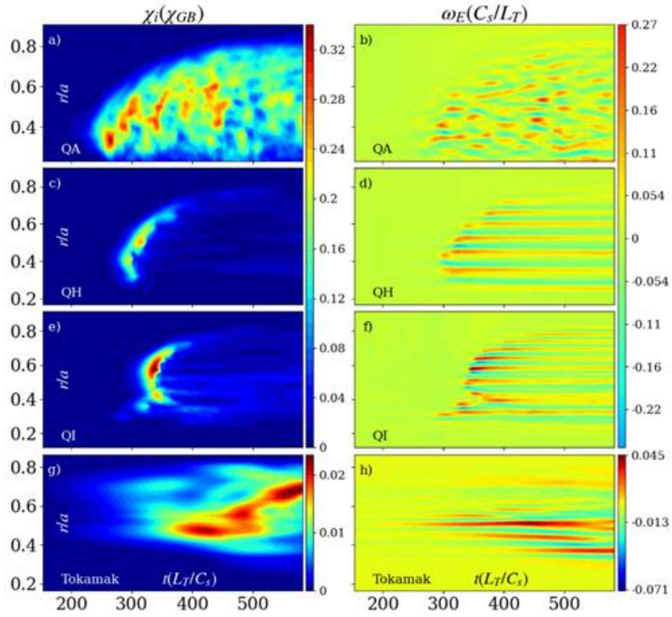

FIG.2: *Time evolutions of the radial profiles of ion*

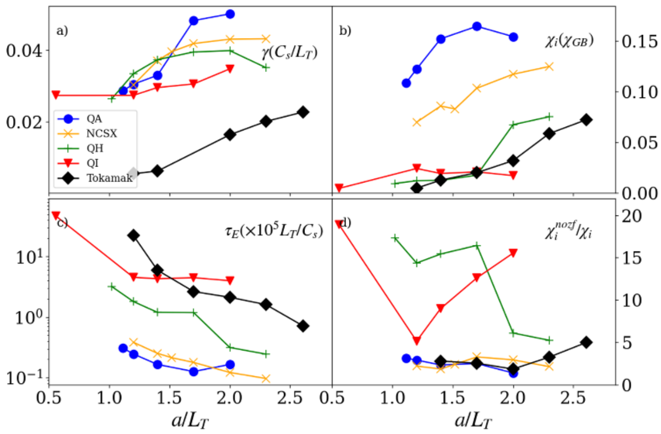

FIG. 3: *Dependence of linear growth rates γ (panel a), heat conductivity χ_i (panel b), confinement times τ_E (panel c), and reduction by zonal flows (panel d) on temperature gradients.*

Dynamics of zonal flows—The zonal flows generated by turbulence are damped to a residual level by the collisionless magnetic pumping effects [7]. This quasi-static zonal flow residual saturates the instability and suppresses the turbulent transport in the quasi-steady state. Linear GTC simulations and gyrokinetic theory [8] find higher residual levels in the QH and QI than the QA and tokamak.

Another important feature in FIG.2 is that the nonlinear frequency of zonal flows in the QA (and NCSX) is much higher than the QH and QI indicating a stronger nonlinear instability [9] of zonal flows in the QA.

Transport scaling— We study the dependence of the transport levels and confinement times on the temperature gradient. As shown in FIG. 3 (a), the linear ITG growth rates γ of the tokamak are much smaller than all the stellarators. However, the ion heat conductivities χ_i of the tokamak are comparable to the QH and QI (panel b). The QA (and NCSX) heat conductivities are much larger. The QH and QI have energy confinement times comparable to the tokamak.

The reductions of heat conductivity χ_i^{nozf}/χ_i by zonal flows are shown in FIG. 3 (d). Here the heat conductivities χ_i^{nozf} are measured in simulations without zonal flows. The reductions in the QH and QI are much bigger than the QA and tokamak.

TEM transport— We have also performed TEM simulation with the same density gradient R/L_n in all devices. The result shows similar zonal flow effects on the electron turbulent transport. Specifically, the QH stellarator has two times larger linear growth rate compared to the NCSX, but the resulting transport is similar due to the larger zonal flow suppression of the turbulence in the QH.

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