Lagrangian statistics of heavy impurity transport in drift-wave turbulence

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We report key findings from direct numerical simulations of tungsten impurity (W) transport in drift-wave turbulence, highlighting the impact of inertia on clustering and anomalous transport. The Stokes number (St), defined as the ratio of particle relaxation time to the characteristic timescale of turbulence, plays a crucial role in impurity behavior [1, 2]. It governs spatial intermittency, leading to the clustering of impurities in turbulent flows (Figure 1): as St increases (St = 0.03, 0.20, 0.83), particle inertia begins to dominate, leading to clustering in regions of low vorticity due to Coriolis force. At high Stokes numbers (St = 9.14), the impurity particles exhibit more ballistic motion, resulting in reduced clustering.and influences their transport dynamics. The mean square displacement (MSD) $\langle r^2(t) \rangle$ as a function of time measures how far, on average, particles move from their initial position over time. The two dashed lines in Figure 2 mark reference slopes for diffusive ($\langle r^2(t) \rangle \propto t$) and superdiffusive ($\langle r^2(t) \rangle \propto t^{1.3}$) regimes. The observed superdiffusion suggests that tungsten ions can spread faster, increasing the risk of core contamination in fusion devices.

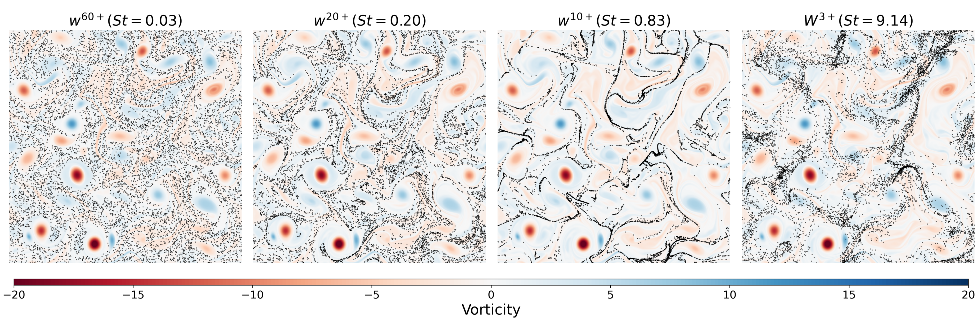

Figure 1. Vorticity fields with 10^4 impurity particles superimposed for $W^{60+}(St = 0.03)$, $W^{20+}(St = 0.20)$, $W^{10+}(St = 0.83)$ and $W^{3+}(St = 9.14)$ in the hydrodynamic regime (c = 0.01).

Tungsten, a key material for plasma-facing components in fusion devices like ITER, plays a critical role in plasma performance due to its high atomic number and significant inertial effects. Tungsten impurities can accumulate in the plasma core, where it enhances radiative losses and degrades confinement. Understanding its transport mechanisms is thus crucial for impurity control strategies in future fusion reactors. While previous studies have analyzed passive flow tracers in drift-wave turbulence, meaning they move exactly with the turbulent flow, neglecting inertial effects [4–6]. Such approximations may suffice for light impurities but are inadequate for heavy impurities like tungsten. In this work, we present a novel derivation of the relaxation time for heavy impurities assuming heavy impurities lag behind plasma flow due to their significant inertia, the relaxation time characterizes how quickly the impurities match the flow velocity. We perform direct numerical simulations of the Hasegawa–Wakatani model to track ensembles of inertial charged impurity particles over hundreds of eddy turnover times in statistically stationary turbulence. The results reveal that inertial effects of tungsten lead to complex behaviors, including clustering and superdiffusive transport, that are not captured by conventional models. Using Lagrangian statistics—including mean squared displacement, scale-dependent curvature angles of the trajectories [3], etc.—we demonstrate the impact of the Stokes number on impurity dynamics. This work represents a novel contribution to fusion plasma research by providing a detailed investigation of these inertial effects and advancing our understanding of tungsten's anomalous turbulent transport.

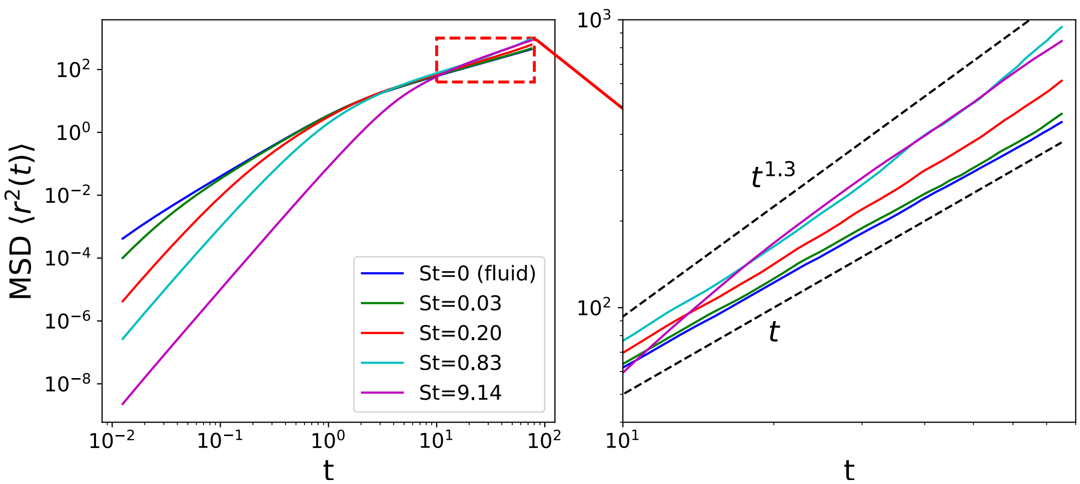

Figure 2. Mean squared displacement of $W^{60+}(St = 0.03)$, $W^{20+}(St = 0.20)$, $W^{10+}(St = 0.83)$ and $W^{3+}(St = 9.14)$.

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