Similarity for downscaled kinetic simulations of electrostatic plasmas: Reconciling the large system size with small Debye length

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First-principles kinetic plasma simulations, with either the Particle-In-Cell (PIC) or the continuum approach, can provide critical insights into complex plasma dynamics and have served as a cornerstone of high-fidelity plasma modelings. They are particularly in demand for nearly collisionless plasmas, where the plasma mean free path is much longer than the characteristic system size. However, these high-fidelity kinetic simulations can incur extreme computational costs, which comes about because the kinetic simulation has to reconcile a large system size with the small plasma Debye length, due to either the physics fidelity requirement in physical systems where a localized non-neutral plasma structure is present in an otherwise quasi-neutral plasma or the demand of PIC simulations to suppress the inherent numerical instabilities.

In order to resolve this issue, we proposed a downscaled approach, from the perspective of similarity, for the kinetic simulations of plasma transport. It can effectively reconcile the tiny Debye length with the vast system size. This applies to both transport in unmagnetized plasma and parallel transport in magnetized plasmas, where the characteristics length scales are given by the Debye length, collisional mean free paths, and the system or gradient lengths. The controlled scaled variables are the configuration space, $\mathbf{x}/\mathcal{L}$, and an artificial Coulomb Logarithm, $\mathcal{L}\ln\Lambda$, for collisions, while the scaled time, $t/\mathcal{L}$, and electric field, $\mathcal{L}\boldsymbol{E}$, are automatic outcomes. The similarity properties are examined, demonstrating that the macroscopic transport physics is preserved through a similarity transformation while keeping the microscopic physics at its original scale of Debye length. Several examples of 1D plasma transport problems using the VPIC code will be discussed to showcase the utility of this approach, including the plasma thermal quench in tokamaks[1,2] and the plasma sheath in the high-recycling regime[3].

References:

[1] Li *et al.*, Nuclear Fusion **63**, 066030 (2023)

[2] Mao *et al.*, arXiv:2311.09396 (2024)

[3] Li *et al.,* Physics of Plasmas **30**, 063505 (2023)