

Charge-Conserving Time Extrapolation of Dynamical Data in Kinetic Plasma Particle-in-Cell Simulations

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In recent years, data-driven methods have found applicability in the modeling of nonlinear complex dynamical systems with unknown or partially known physics. Dynamic mode decomposition (DMD) is a data-driven reduced-order technique that constructs a best-fit linear system by learning the time-evolution from a limited set of training data generated from the dynamical system of interest. From the constructed reduced-order model, DMD is capable of rapid time-extrapolation, valid beyond the generated training data. Recently, DMD has been shown to be effective in the modeling of kinetic plasmas [I. Nayak, F. L. Teixeira, D.-Y. Na, M. Kumar, and Y. A. Omelchenko, “Accelerating particle-in-cell kinetic plasma simulations via reduced-order modeling of space-charge dynamics using dynamic mode decomposition,” *Phys. Rev. E*, vol. 109, no. 6, p. 065307, 2024]. The model of interest consists of the discretized Vlasov-Maxwell system based on a finite-element particle-in-cell formulation [D.-Y. Na, H. Moon, Y. A. Omelchenko, and F. L. Teixeira, “Local, explicit, and charge-conserving electromagnetic particle-in-cell algorithm on unstructured grids,” *IEEE Trans. Plasma Sci.*, vol. 44, no. 8, pp. 1353–1362, 2016]. DMD is capable of charge, current, and field data time-extrapolation from the full-order simulation. The issue to be addressed here is the following: Although DMD is successful in time-extrapolation of the mentioned quantities, significant loss of accuracy occurs in the discrete continuity equation, relating current and charge on the mesh.

With respect to the continuity equation residual, the significant discrepancy between the two models can be attributed to the fact that DMD is applied to charge and current data independently from each other, unconstrained from the discrete continuity equation. We propose integration of the continuity relation with a DMD-based model in order to retain charge-conservation from the full-order simulation. Preliminary results based on cavity plasma examples suggests that utilization of the continuity equation integrated with a single DMD model for both charge and current is effective in delivering a charge-conserving reduced-order model.