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Abstract for an Invited Paper
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Structure-Preserving, Geometric, Particle-in-Cell Algorithms for Tokamaks[1]

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Recently, structure-preserving, geometric discretization methods have been applied across a wide range of fields, including plasma physics, fluid dynamics, and astrophysics. Structure-preserving geometric algorithms preserve the geometric structures of the physical systems, such as Poincare symmetry and local energy-momentum conservation, gauge symmetry and charge conservation, and symplectic structure and phase space volume. They are especially suited for exascale computing hardware. They possess the long-term accuracy required, but unavailable using conventional algorithms, in the study of the multi-scale, complex dynamics of space and laboratory plasmas [PRL 100, 035006]. To preserve the symmetries and geometric structures of physical systems in discrete space-time lattices, the new algorithms utilize modern mathematical techniques, such as discrete manifold, interpolating differential forms, and non-canonical symplectic integrators [PoP 22, 124503]. The talk will focus on the recent development of the structure-preserving geometric Particle-in-Cell (PIC) algorithms [PoP 19, 084501; PoP 22, 112504; NF 56, 014001; NF 59, 106044], whose advantages are now apparent in a variety of important problems. For example, the long-term accuracy and fidelity of the algorithms made possible the first-ever whole-device 6D kinetic simulations of tokamak physics [arXiv:2004.08150] and enabled us to confirm numerically, over several orders of magnitude, Villani's Fields-Medal-winning theory on nonlinear Landau damping. In addition to the new generation of PIC methods, MHD simulations using the structure-preserving algorithms have now provided the strongest numerical confirmation so far of Parker's conjecture of current singularity. And structure-preserving algorithms for the Klein-Gordon-Maxwell system enabled the first real-time lattice QED simulations of laser-plasma interactions. These important developments and discoveries will be systematically reviewed as well.

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