Grid-Based Methods for Simulating Electromagnetic Waves in Collision Free Plasmas

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The problem of simulating electromagnetic waves in collision-free plasmas is a mature but active area of research. In general, the problem requires tracking a distribution of charged particles in phase-space while self-consistently computing the electromagnetic fields that are produced. The complete mathematical description is given by the Vlasov-Maxwell system of equations, which has typically been computational expensive to solve. However, modern high performance computing (HPC) resources now permit completely kinetic or hybrid plasma simulations that may have not been possible just a decade ago.

In recent years, particularly in the space plasma modeling community, Particle-in-Cell (PIC) codes have been successfully utilized to solve the Vlasov-Maxwell system and explain complex plasma wave behavior. PIC simulations rely on following a large number of macro-particles while simultaneously computing the fields that are generated. The error in PIC simulations is inversely proportional to the square root of the number of macro-particles and hence requires a large number of macro-particles to reduce sampling noise. While PIC simulations are indeed powerful and indispensable, HPC resources now also permit alternative numerical approaches. In contrast to PIC, methods that rely on computing the particle distribution function directly on a phase-space grid can produce much higher contrast and provide fine information in phase-space.

Semi-Lagrangian (SL) and Eulerian methods are numerical formalisms that rely on directly computing the particle distribution function on a known phase-space grid. In problems where particles in known regions of phase-space are believed to be the primary contributors to wave production (such as resonances), utilizing grid-based approaches can decrease computational time and improve accuracy. Although grid-based methods have been utilized for modeling waves in space plasmas, the existing codes typically rely on narrowband assumptions, low order interpolation, and artificial filtering. We consider an extension of grid-based methods for space plasma modeling by utilizing higher order interpolation and relaxing narrowband assumptions. The advantages and disadvantages of grid-base methods relative to PIC are evaluated in the context of simulating waves in space plasmas for both narrowband and broadband problems. Although space plasmas are considered in particular, the simulation techniques carry over naturally to other collision free plasmas.