Low-noise, time-implicit PIC methods[1]

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In earlier work,[2] a time-implicit, energy conserving δf PIC algorithm was described and results presented for linear instability of the g-mode. Key features of this IMP (Implicit Moments and Particles) approach are implicit moment/Maxwell equations evolving the number density and fluid velocity per species, the use of the particular velocity to obtain symmetric, energy-conserving equations, a closure stress computed from δf including the fluctuation temperature contribution, and orbit averaging to represent multiple time scales. Present work extends this earlier algorithm to fully non-linear capability and examines its performance for a number of conventional and unconventional δf applications in one and two-dimensions.

New features which have been developed and are described are: 1) Particle moving is done by the usual leap-frog Boris mover using the implicit EM fields. The particular velocity is advanced independently; 2) A new projection method is used to eliminate finite particle number truncation errors in the closure moments and assure energy conservation to roundoff; 3) The role of various moment advance schemes are investigated.; 4) The implicit solve is greatly simplified by slaving all moment quantities to the time-advanced velocity fields and solving for these with a Jacobian-Free Newton-Krylov method.

Conventional δf applications include both the Langmuir wave and the ion-acoustic wave where excellent agreement with both real frequency and Landau damping are obtained. As an example of a strongly non-linear, strongly inhomogeneous problem, the electron cold two-stream instability is computed with the non-linear IMP δf method. The time evolution of this mode is tracked past the wave breaking phase and shows the usual saturation *via* electron trapping. Charge, momentum, and energy conservation are excellent, in agreement with analytic expectations.

A two-dimensional, electromagnetic formulation of IMP is also described and its application to g-mode turbulence is demonstrated by following linear instabilities past saturation. The extension to the case of significant background temperature gradient is shown to be accomplished by describing the background as an evolving mixture of uniform T fluids. We conclude that the IMP approach is a promising algorithm for simulation of non-linear low-frequency plasma instability phenomena (turbulence) and is compatible with present and near-term computer architectures.

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[2] D. C. Barnes, J. Cheng, and S. E. Parker, *Phys. Plasmas* **15**, 055702 (2008).