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A Lagrange-Maxwell solver for the PIC simulation of the plasma environment of Mercury

Jorge Amaya (1), Diego Gonzalez-Herrero (1), Bertrand Lembège (2), and Giovanni Lapenta (1)

(1) KU Leuven, CmPA, Mathematics, Leuven, Belgium (jorge.amaya@wis.kuleuven.be), (2) LATMOS-IPSL-UVSQ-CNRS, Guyancourt, France

An intrinsic drawback of the Particle-in-Cell method is the quality of the statistics extracted from a small particle population. At the orbit of Mercury, the particle number density is $10^{21}\ d_i^{-3}$. However, the most powerful PIC codes today feature a maximum macro-particle number density of $10^3\ d_i^{-3}$. In addition, the interpolation of the information from the particles to the grids is performed using a low order b-spline shape function (most commonly a linear interpolation). As a result the moments of the velocity distribution, obtained from the small particle population, are noisy.

This noise translates as spurious charge densities and currents in the Maxwell equations, leading to the formation of electrostatic fields in the direction of velocity anisotropy, e.g. in the direction of a plasma drift or a current. This numerical instability grows in time, independent of the physical properties of the plasma. This is known as the finite-grid instability, and is often controlled using a smoothing function that softens the noise in the electromagnetic fields in the Maxwell solver. However, simulations of planetary plasmas using large Δt and Δx are much more susceptible to this instability and smoothing methods show no positive results.

There are two main approaches to improve the statistics of the problem: one is to build a method in which the velocity distribution is transported instead of moving individual macro-particles. The second solution is to heavily increases the number of macro-particles in the PIC code, using the brute compute power of modern massively parallel hardware.

But there is a low cost alternative: instead of improving the statistics, we can avoid the initial anisotropy of the problem. In the case of the Mercury PIC simulations, the solar wind plasma is injected in one of the boundaries of the simulation box with a constant drift velocity. To avoid the growth of the instability in this direction we solve the Maxwell equations on a Lagrangian frame of reference that moves with the drifting plasma. In this frame of reference the particle velocity distribution is isotropic and creates no instability in the direction of drift. The induced spurious charge densities and currents created by the anisotropies are replaced by a Lorentz transformation that takes into account the constant background drift of ions and electrons.

In this presentation we show how this improvement allows to dispose of the numerical instability. We present details of the algorithm used and how the particle and the field solvers interact. We present simulations of the environment of Mercury using the Energy Conserving PIC code ECsim, featuring a Lagrange-Maxwell solver. We extend the spatial and time resolutions to resolve the physics at the planetary scales without loosing the dynamics of ions and electrons. We capture the formation of the bow shock, the complexity of the inner-magnetosphere and we reproduce the asymmetries of the Kelvin-Helmholtz instabilities observed in the equatorial plane.

This method can be used for applications requiring the study of multiscale processes, including self-consistent simulations of the solar wind and planetary magnetospheres.