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ELECTROMAGNETIC "PARTICLE-IN-CELL" PLASMA SIMULATION†

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"PIC" simulation tracks particles through electromagnetic fields calculated self-consistently from the charge and current densities of the particles themselves, external sources, and boundaries. Already used extensively in plasma physics, such simulations have become useful in the design of accelerators and their rf sources.

I. INTRODUCTION

PIC plasma—simulation models use a spatial grid to mediate the electromagnetic interactions between particles. Charge and current densities are formed from the particle coordinates onto a spatial grid. Using partial-difference equations on this grid, an electric field is found. Then the particles are individually advanced in time using classical equations of motion with the acceleration found by interpolation from the electric and magnetic fields on the grid. Used in some form in almost all modern plasma work, this method is not only faster than summing over particle interactions, but it also avoids very large transient accelerations of closely spaced particles, which create complications irrelevant to the simulation of collective effects in weakly collisional plasmas.

Two recent books[1,2] cover most aspects of this type of simulation and its elaborations, together with many applications, and provide a large collection of references to original papers and to other work. Here I outline the principal forms of electromagnetic codes and their applications, first in plasma physics and then to accelerators.

II. SIMULATIONS WITH FULL ELECTROMAGNETIC FIELDS

With an appropriate space and time differencing of the Faraday and Ampere–Maxwell equations, the particle motion is coupled to light or microwaves. Usually in such codes the particle motion is fully relativistic. Major motivations for these codes have been simulation of interaction of intense laser light and of intense electron beams with hot plasmas, involving wave-particle resonances, trapping,

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and other kinetic effects. Modeling these physical processes requires a particle-tracking method rather than a fluid description.

III. MAGNETOINDUCTIVE (DARWIN) FIELDS

In terms of a code using fields, the interactions given by Darwin's retardationless Lagrangian are equivalent to dropping Maxwell's transverse displacement—current term. These "pre-Maxwell" equations eliminate electromagnetic—wave propagation while retaining electrostatic, magnetostatic, and inductive electric fields. Darwin codes are useful for simulations of low-frequency phenomena for which a Courant time-step limitation imposed by light-transit times would be onerous in an explicit code. Often in a hybrid form using particle ions and fluid electrons, these codes have been used to simulate instabilities and shocks in magnetized plasmas in the laboratory and in space.

IV. IMPLICIT TIME INTEGRATION

Implicit time differencing of the Maxwell equations retains EM wave propagation at long wavelengths ($\gg c\Delta t$). At short wavelengths, the electrostatic, magnetostatic, and inductive electric fields are retained, as in a Darwin code. With implicit time differencing of the particles, time steps much larger than the electron plasma period ω_{pe}^{-1} can be used, permitting economical modeling of low-frequency ($\ll\omega_{pe}$) phenomena with spatial-scale lengths longer than electron time-step transit distances ($v_e\Delta t$). These codes partially subsume the full-electromagnetic and Darwin codes but are more complicated to write and use. Developed relatively recently, they open new parameter regimes to the computational physicists.

V. APPLICATIONS TO ACCELERATORS AND RF SOURCES

Compared to most applications in plasma physics, these involve more complicated geometries but are less demanding in numbers of particles required. Because the interaction length in a non-neutral plasma tends to be a large fraction of the size of the system, good statistics are obtained with a relatively smaller number of particles than are needed in applications to neutral plasmas, in which the interaction lengths (Debye length, electromagnetic skin depth, . . .) are usually much smaller than the size of the system.

The MASK code was developed originally to model relativistic magnetrons.[3] Using methods described in Chapter 15 of Ref. 1, together with many prescriptions for particle emission and absorption at surfaces, ports to rf cavities, etc., MASK and its descendants have been used to model behavior of high-power klystrons[4] and the buncher for the SLAC Linear Collider.[5] It is anticipated that computer modeling will lead to higher optimization of these devices.

VI. REFERENCES

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