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Theoretical and numerical approaches for Vlasov–Maxwell equations

Foreword

Charged particle beams and plasma physics problems are extensively used in Science and Technology. The main application of this branch of physics is in microwave electronics (including plasma microwave electronics), high-current accelerators, and nuclear radiation. Particles accelerators have also found some use in medicine, mainly but not solely for the treatment of cancer.

Indeed, modern radiotherapy achieved its successes as a result of the advances that were introduced in the linear accelerator technology and computerization, making radiation-dose delivery extremely sophisticated.

As a consequence, there is an increasing need for finding realistic mathematical models of such beams that can be used for numerical simulations. If we restrict ourselves to collisionless plasma or non-collisional beams, the most complete mathematical model is provided by the time-dependent Vlasov–Maxwell equations that are the collisionless limit plasma model of Boltzmann–Maxwell equations.

Unfortunately, this model leads to very expensive computations, usually implemented by particle-in-cell-type methods (PIC). Although the direct numerical approximation of Vlasov–Maxwell equations is unavoidable in a number of cases, simpler models may be used in many situations.

In particular, when dealing with the transport of charged particle beams, one can try to use paraxial models that exploit the property of the particles of the beam to remain close to an optical axis, therefore implying that their transverse velocities might be neglected. In this case, many asymptotic models have also been developed to significantly reduce the cost of numerical simulations that correspond to the complete solution to Vlasov–Maxwell equations.

At the high beam currents and charge densities of practical interest, of particular importance are the effects of the intense self-fields produced by the beam space charge and current on determining the detailed equilibrium, stability and transport properties, and the nonlinear dynamics of the system.

Through analytical studies based on the nonlinear Vlasov–Maxwell equations for the particles distribution function and the self-generated electromagnetic field, and numerical simulations using particle-in-cell models and nonlinear perturbative simulation techniques, considerable progress has been made in developing an improved understanding of the collective processes and nonlinear beam dynamics characteristic of high-intensity beam propagation in periodic focusing and uniform focusing transport systems.

Also, numerical simulations of mathematical models describing charged particle beams have considerably grown over the past two decades, particularly with the development of particle accelerators, the Free Electron Laser, etc. The purpose of these simulations is to gradually replace the experiments of calibration of these processes, and to provide assistance in determining the appropriate settings for the relevant applications.

These simulation tools are usually built by solving Vlasov–Maxwell equations for complex geometries in dimension 2 or 3. In this context, Vlasov's equation is generally solved by a particle method that consists in representing the particle beam by a number of macro-particles, then by computing their displacements with the dynamics law.

The calculation of the electromagnetic field is achieved by solving Maxwell's equations by finite-difference methods on regular meshes for simple geometries, or by (continuous or discontinuous) finite-element or finite-volume methods for unstructured meshes, in the case of more complex geometries.

This thematic issue proposes a set of papers that present several of the above-discussed topics.

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