Modeling of Counter Streaming Charged Beams in MICHELLE–eBEAM*

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Abstract:
The simulation of counter streaming charged particle beams, where two beams are co-located in space while propagating in opposite directions, has many applications in high current electron beam nanolithography. These applications often require the modeling of both global and stochastic space charge, where the latter calls for direct evaluation of Coulomb interactions. A new approach implemented in the MICHELLE-eBEAM code is designed to take advantage of the GPU hardware acceleration and novel algorithms to capture such inter-particle interactions efficiently. In this paper we report on our latest progress and demonstrate for a high current electron beam lithography application the achieved accuracy and performance of the new code.

Keywords: eBEAM, MICHELLE, GPU, Coulomb, lithography, stochastic space charge, counter streaming.

Introduction

The MICHELLE [1], [2] two-dimensional (2D) and three-dimensional (3D) steady-state and time-domain electrostatic particle-in-cell (PIC) code has been employed successfully by industry, national laboratories, and academia and used to design and analyze a wide variety of devices, including multistage depressed collectors, RF photocathodes, inductive output tube (IOT) guns, gridded guns, multibeam guns, annular-beam guns, sheet-beam guns, beam-transport sections, and ion thrusters.

Electron and ion beam simulations such as those applicable to charged particle beam nanolithography pose additional challenges to modeling software due to the requirement to achieve high accuracy. Disparate spatial scales in such devices put unrealistic constraints on mesh size in mesh-based simulations. In order to achieve high accuracy over large distances, a different approach is necessary to represent both externally imposed static fields as well as self fields resulting from global and stochastic space charge effects. A mesh-less based solution has been chosen in MICHELLE-eBEAM [3], where inter-particle effects are captured using direct Coulomb interactions. Large particle count is needed to resolve inner-beam dynamics. In addition, simulating counter streaming beams puts much higher demands on the number of particles required in the simulation. An efficient algorithm coupled with GPU hardware acceleration provides the necessary computational power to tackle the problem.

Approach

The approach taken in MICHELLE's eBEAM module to meet the externally applied field accuracy requirement is to employ an analytical expansion of electrostatic and magnetostatic fields calculated using finite element methods. High accuracy particle tracking calculations are accomplished by using explicit time integrators such as Dormand-Prince with adaptive time step size control to solve the relativistic Lorentz equation of motion.

Explicit pair-wise calculation of Coulomb particle-particle interactions has $O(n^2)$ computational complexity and a tree algorithm reduces the complexity to $O(n \log n)$ and makes the force calculation feasible for large particle counts. In the MICHELLE-eBEAM module efficient evaluations of Coulomb interactions are accomplished by using high performance GPU hardware which acts as a co-processor to the host CPU-based program.

Modeling counter streaming beams can easily double or quadruple the number of particles involved in the simulation. The counter streaming inter-particle interaction time could range from a relatively long-term to the short-term (fly-by) time scale. For our application in high current nanolithography the regime is dominated by the short fly-by interaction times. Examples will be presented that demonstrate the features and capabilities of the code.

References

1. John Petillo, et al., "The MICHELLE Three-Dimensional Electron and Collector Modeling Tool: Theory and Design", IEEE Trans. Plasma Sci., vol. 30, no. 3, June 2002, pp. 1238-1264.
2. John Petillo, et al., "Recent Developments in the MICHELLE 2D/3D Electron Gun and Collector Modeling Code", IEEE Trans. Electron Devices Sci., vol. 52, no. 5, May 2005, pp. 742-748.
3. Serguei G. Ovtchinnikov, et al., "High accuracy electron beam model development in MICHELLE: eBEAM", J. Vac. Sci. Technol. B **28**, C6J8 (2010).

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