MODULATOR SIMULATIONS FOR COHERENT ELECTRON COOLING

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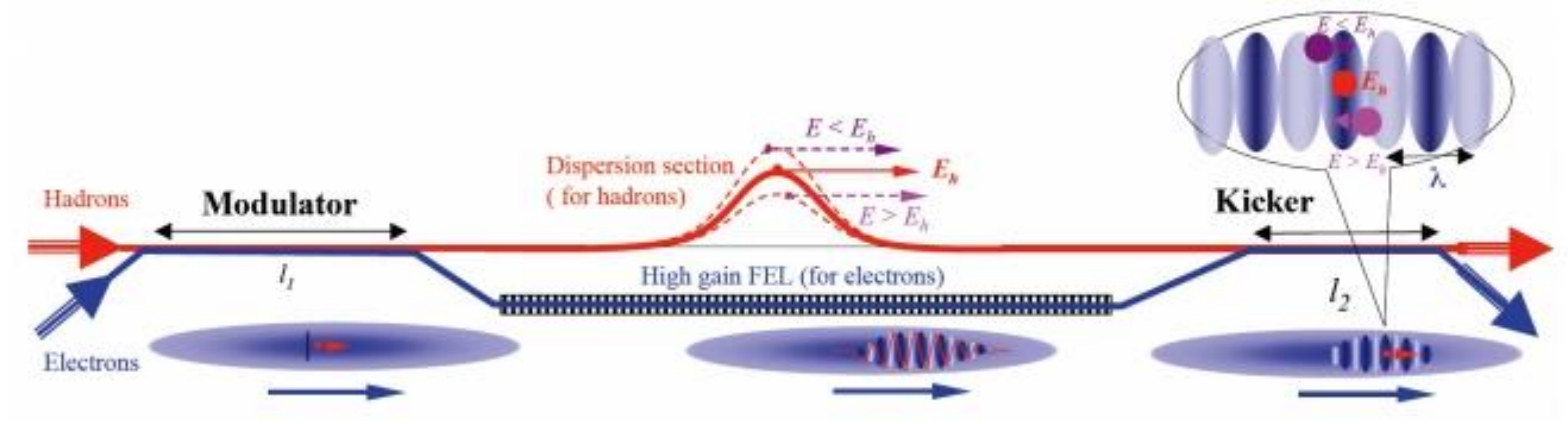
Abstract

Highly resolved numerical simulations of the modulator, the first section of the proposed coherent electron cooling (CEC) device, have been performed using the code SPACE. The beam parameters for simulations are relevant to the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Numerical convergence has been studied using various numbers of macro-particles and mesh refinements of computational domain. A good agreement of theory and simulations has been obtained for the case of stationary and moving ions in uniform electron clouds with realistic distribution of thermal velocities. The main result of the paper is the prediction of modulation processes for ions with reference and off-reference coordinates in realistic Gaussian electron bunches with quadrupole field.

Introduction

Coherent electron cooling (CEC) **[1,2]** consists of three sections:

- Modulator, ion imprints a density wake electron distribution.
- Amplifier, density wake is amplified.
- Kicker, amplified wake interacts with ion, resulting in cooling.



A general schematic of CEC.

Beam parameters for numerical simulations are relevant to Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL).

Parameters of electron and ion beams

	Electron	Ion, $\mathbf{Au}^{+79}$
Beam energy	γ=42.9	γ=42.9
Peak current	100 A	
Bunch intensity	10 nC	1e+9
Bunch length	10 ps (full)	2 ns (r.m.s)
R.M.S. emittance	5 π mm mrad	2 π mm mrad
R.M.S. energy spread	1e-3	
Beta function	4 m	

Methods And Tools

SPACE, a parallel, relativistic, 3D EM PIC code **[3]**, has been used for

- study of plasma dynamics in a dense gas filled RF cavities **[4]**.
- study of mitigation effect by beam induced plasma **[5].**

SPACE contains electrostatic module, with two approaches

- Traditional PIC method for Poisson-Vlasov equation. Effective for uniform beam and periodic boundary condition.
- Adaptive Particle-in-Cloud (AP-Cloud) method **[6]**. Mesh is an adaptively chosen set of computational particles. Beneficial for non-uniform beams, geometrically irregular computational domains and mixed type boundary conditions.

SPACE electrostatic module is used for CEC.

Single ion approximation:

- Relative density modulation is orders smaller than unity in relativistic beam energy.
- Treat each ion individually and use superposition principal to obtain net responses of electrons to all ions in the beam.

Motivation:

- Analytical solution exists for uniform spatial distribution **[7]**.
- Numerical approaches needed for spatially non-uniform electrons: Solving the Vlasov equation **[8]**. Direct macro-particle simulation **[9]**.

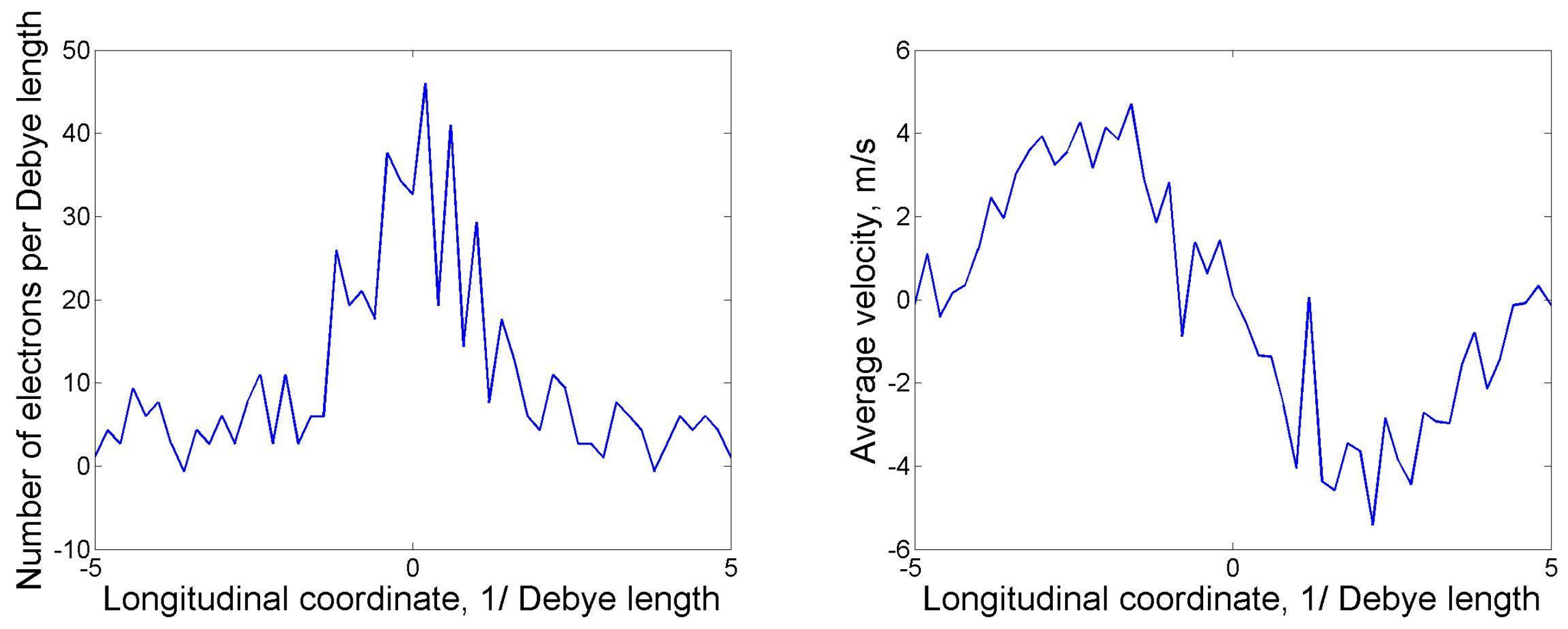
Main challenge:

- modulation signal is too weak compared to the shot noise.

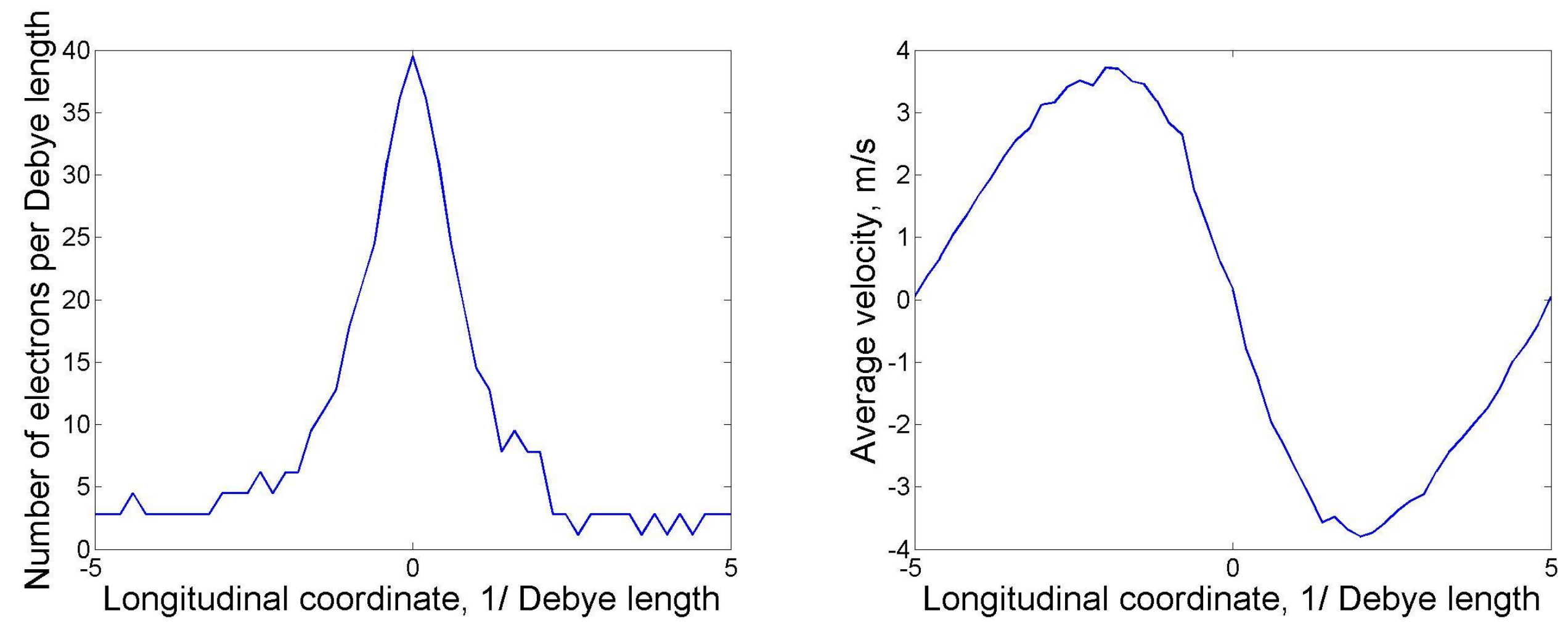
Simulation approach:

- Perform two simulations with identical initial electron distribution.
- One simulation operates only with electron beam.
- The other simulation contains the electron beam and an ion .
- Assume that the ion only slightly changes the trajectories of the electrons over modulator.
- Taking difference in the final electron distributions of the two simulations to obtain the influences of the ion.
- Similar approach has been successfully applied to simulate the FEL amplification process in the presence of shot noise **[10]**.

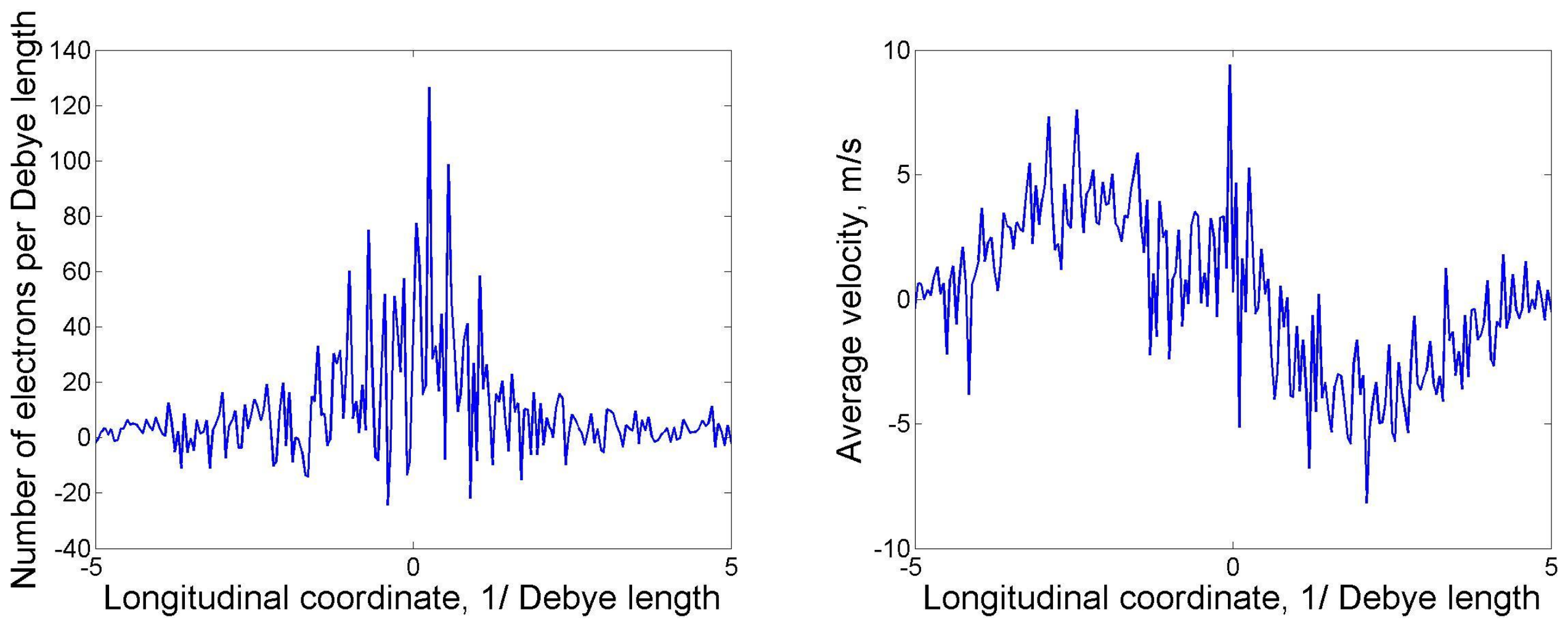
Numerical Convergence



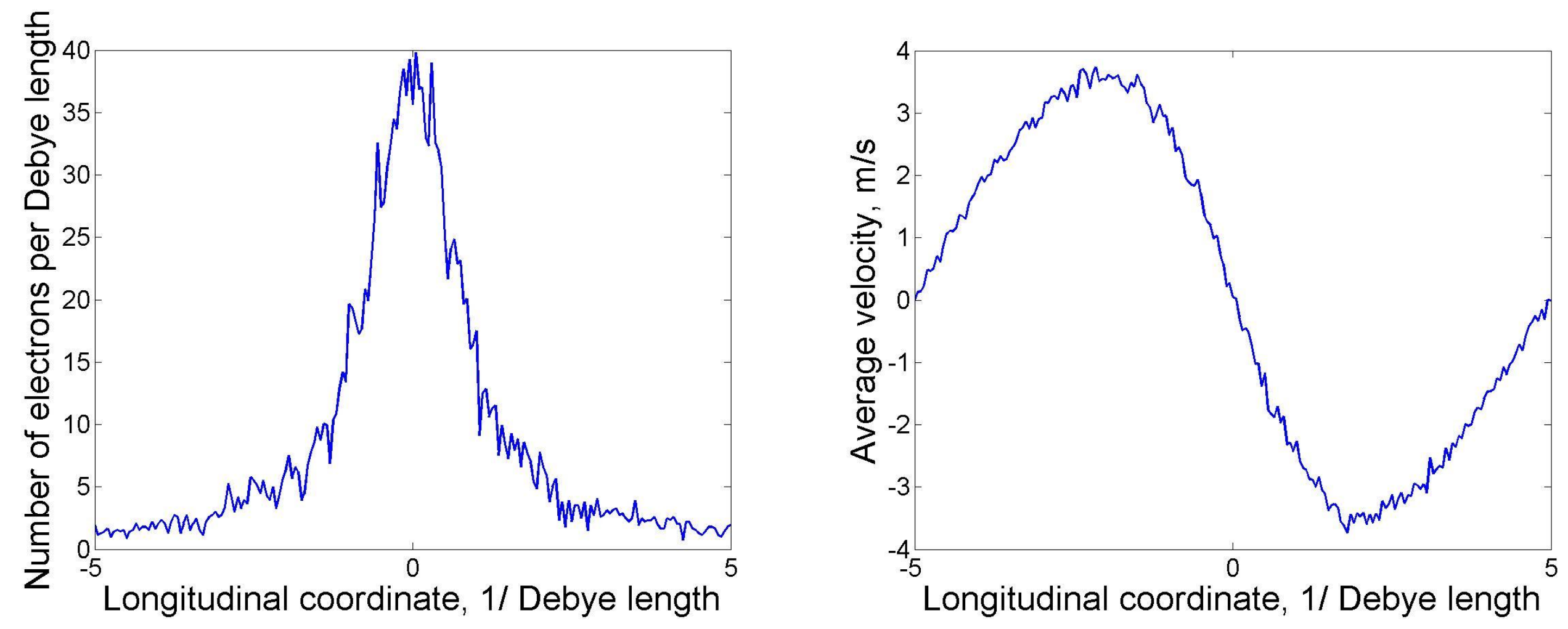
5 grids per Debye Length, 3e+5 macro-particles



5 grids per Debye Length, 3e+7 macro-particles



20 grids per Debye Length, 3e+5 macro-particles

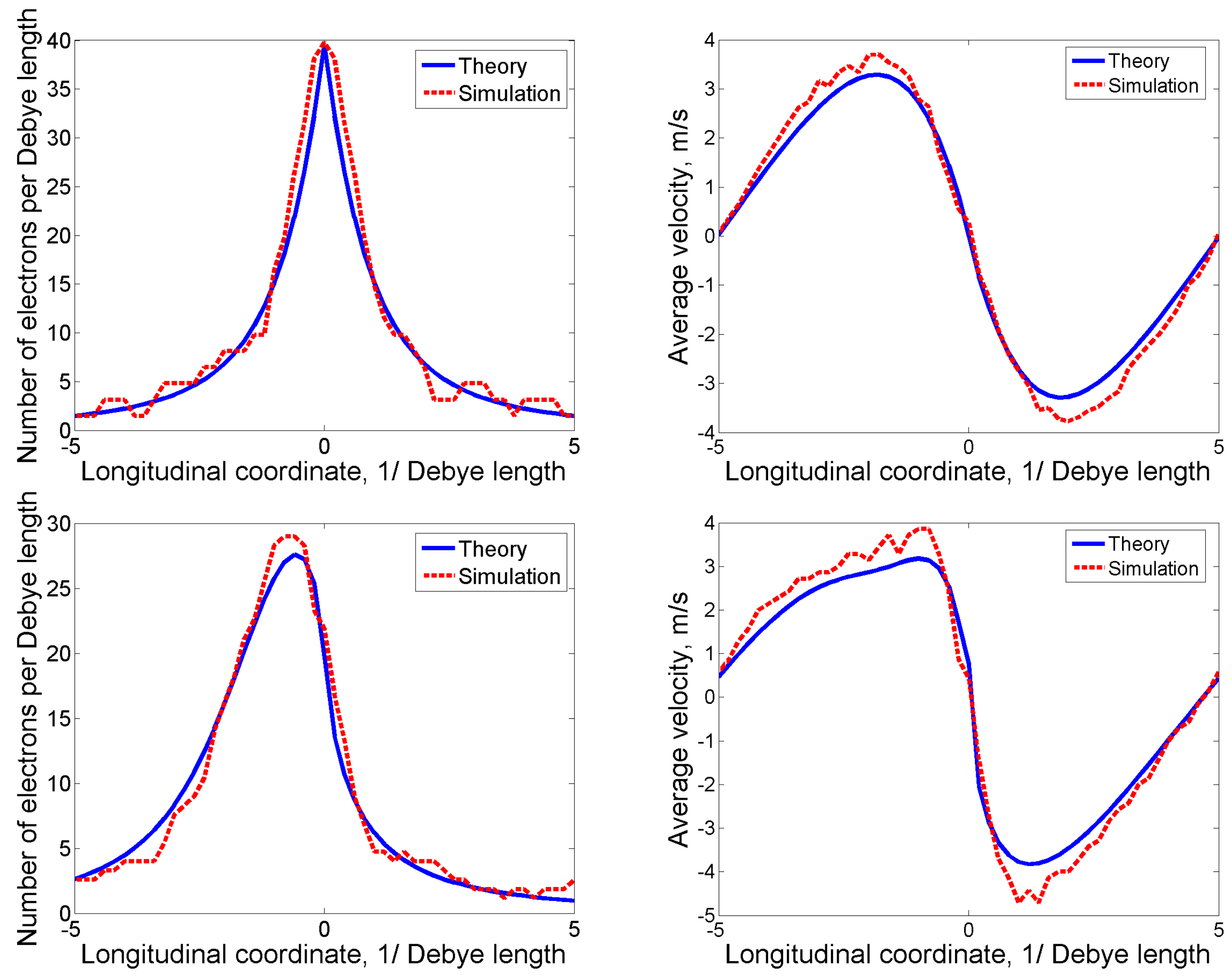


20 grids per Debye Length, 3e+7 macro-particles

Convergence study of longitudinal density (left column) and velocity (right column) modulation with various mesh refinements and numbers of macro-particles.

Verification

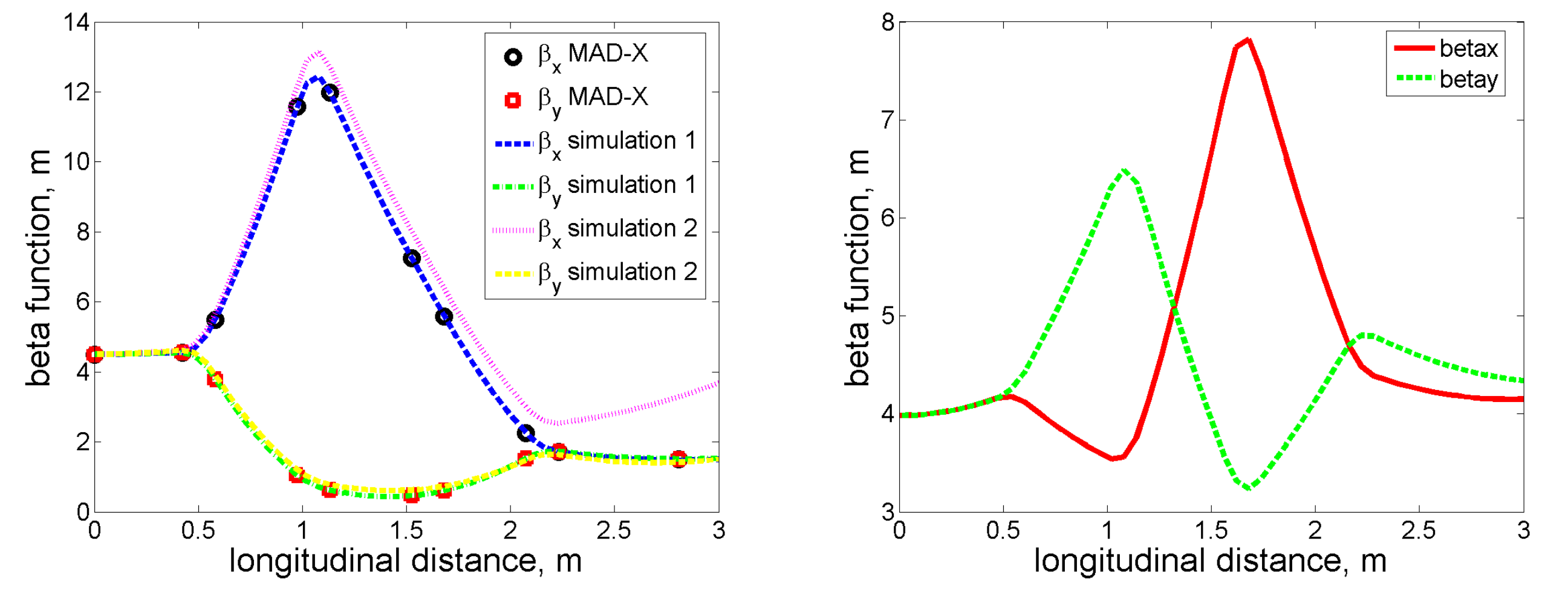
- Use Kappa-2 probability density function to model thermal velocity distribution. 3D form of the density function is given in **[7]**, 1D and 2D forms are given in **[11]**.
- Theoretical values for density and velocity modulation, respectively, are given in **[11]** and **[12]**.



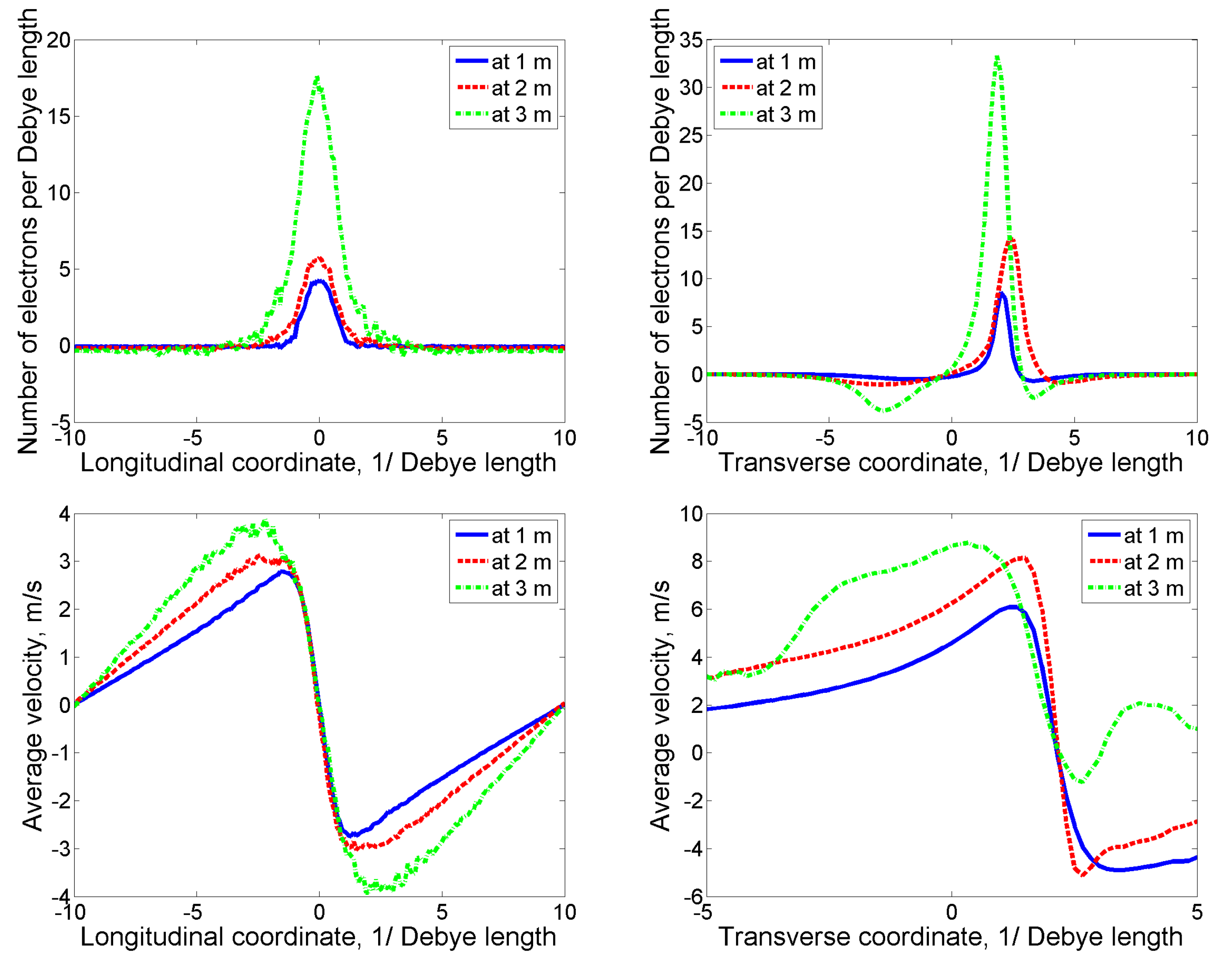
Comparison of theory and numerical simulations of density (left) and velocity (right) modulation by stationary (top) and moving (bottom) ion with respect to uniform electron cloud.

Prediction

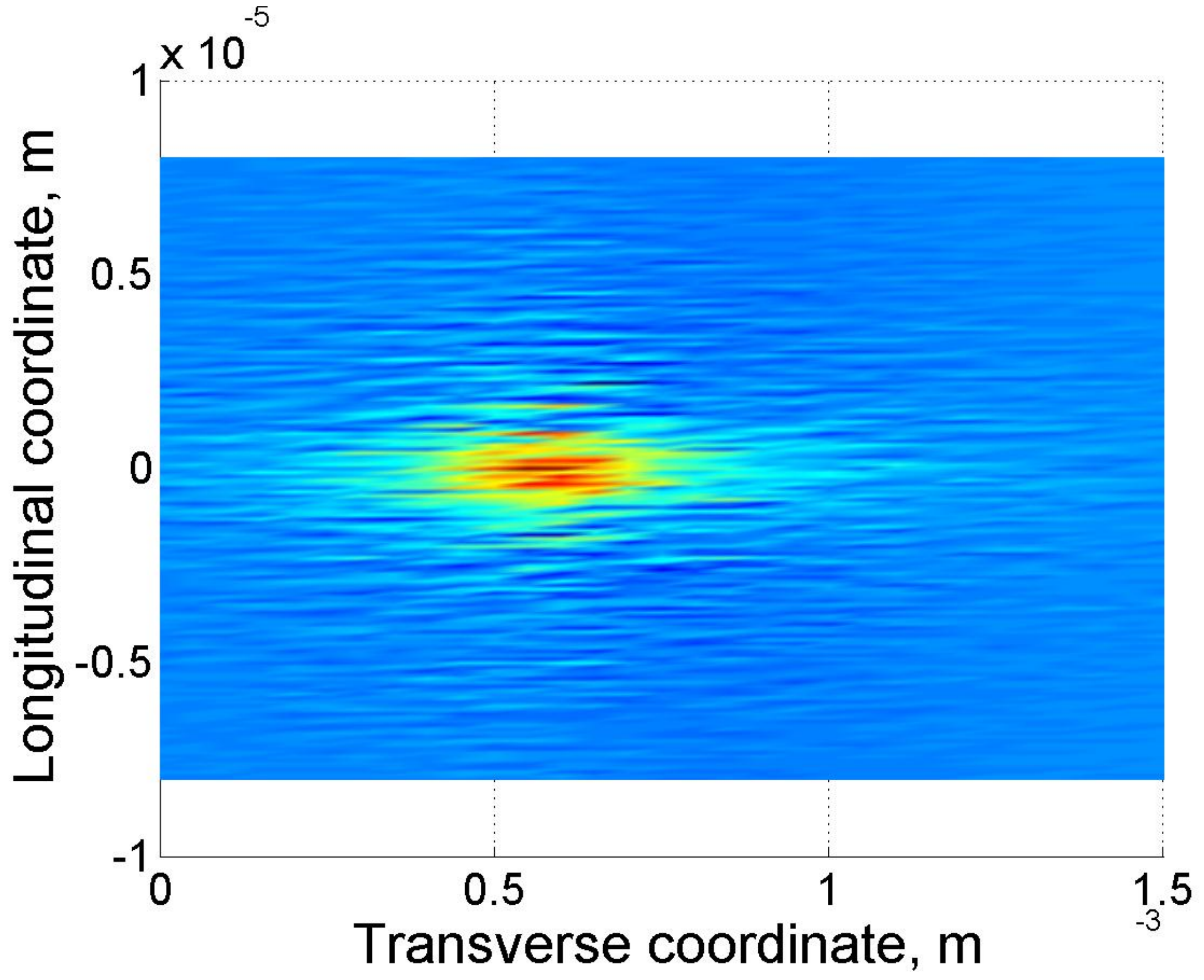
- Gaussian distribution with open boundary condition
- Quadrupoles field with hard edge : $B_y = K \cdot x, B_x = K \cdot y$



Transverse β function changes in quadrupoles magnetic field.
Left: MAD-X is used as benchmark (no space charge effect), simulation 1 uses reduced charge in SPACE, simulation 2 uses regular charge in SPACE, quadrupoles are artificially set to make the β_x and β_y match at the end of quadrupoles.
Right: Quadrupoles magnetic field for modulator simulation uses more realistic setting, and is relevant to RHIC at BNL.



Density (top) and velocity (bottom) modulation in longitudinal (left) and transverse (right) by ion one σ off the center of the Gaussian electron beam in quadrupoles field.



2D plot of density modulation by ion one σ off the center of the Gaussian electron beam in quadrupoles field.

Conclusion

- Numerical convergence shows that our code is self-consistent
- Comparisons with theory in modulation processes and quadrupoles magnetic field effect show that our simulation results are reliable.
- We give prediction for ion co-propagating with Gaussian electron beam in quadrupoles magnetic field

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