Towards Predictive Kinetic Simulations of Hall Thrusters and on Ubiquitous Formation of Solitons

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Igor D. Kaganovich[1], C. Lan[2], Andrew T. Powis[3], Alexander V. Khrabrov[4], Johan Carlsson[5], Yevgeny Raitses[6]
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543 USA

Salomon Janhunen[7], L. Xu[8], Andrei Smolyakov[9]
University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E2, Canada

Dmytro Sydorenko[10]
University of Alberta, Edmonton, Alberta T6G2E9, Canada

Abstract: We study several aspects of plasma thrusters which are needed to be simulated for longer times in a large dimensions and can be only addressed by our upgraded scalable PIC simulations. First study pertains to the ion beam neutralization by emitting electrons at the thruster exit. In 2D PIC simulation studies we found that the capture process of electrons by ion beam can cause the occurrence of the two-stream instability, and more importantly, this instability quickly evolves into stable moving nonlinear electron soliton waves that affect plasma potential. We also observed ion soliton formation when ion beam enters the plasma. For studies of the electron cyclotron drift instability (ECDI) in Hall thrusters we investigated effects of the simulation box size and higher number of particles in cell on resulting anomalous transport. It is found that the instability develops as a sequence of the cyclotron modes demonstrating non-quasineutral large amplitude ion density fluctuations at short wavelengths. The intense long wavelength mode with distinct variations along the magnetic field was identified as the modified two-stream instability leading to strong parallel heating of electrons. In addition, rigorous Validation and Verification procedures are discussed for use by electric propulsion community.

I. Introduction

The need for optimization of Hall thrusters still warrants physics studies of plasma turbulence in acceleration and plume regions. We have modified and substantially upgraded two multi-dimensional high performance particle-in-cell (PIC) codes (EDIPIC and PPPL-modified LSP), which were extensively validated in the past, see e.g., in Ref. [1]. The new parallel codes can effectively use many processors and allow us to perform longer and

[1] Principal Research Physicist, Plasma Science and Technology Department, ikaganov@pppl.gov.
[2] Visiting Research Scientist, Plasma Science and Technology Department, lanchaohui@163.com.
[3] Ph.D. Candidate, Department of Mechanical and Aerospace Engineering, apowis@princeton.edu.
[4] Research Scientist, Plasma Science and Technology Department, akhrabrov@pppl.gov.
[5] Computational Physicist, Computational Plasma Physics Group, carlsson@radiasoft.net.
[6] Principal Research Physicist, Plasma Science and Technology Department, yraitses@pppl.gov.
[7] Computational Physicist, Computational Plasma Physics Group, jjanhune@pppl.gov.
[8] Research Associate, Department of Physics and Engineering Physics, hfxuliang@gmail.com.
[9] Professor, Department of Physics and Engineering Physics, andrei.smolyakov@usask.ca.
[10] Research Scientist, Department of Physics, sydorenk@ualberta.ca

larger 2-3D simulations of discharges, where kinetic and collective effects are important, see e.g. Refs. [2-8]. We also developed a new code that has been designed to study the effects of anomalous transport within ExB discharges. Emphasis was placed on adopting high-performance-computing best practices, to enable scalability up to thousands of cores and therefore simulations of very large domains. The code was shown to possess good weak scaling behavior, and demonstrated that even within idealized simulations of a Hall thruster channel, the resolution of large length scales is critical to fully resolve the physics[9]. Using these codes, we studied several aspects of plasma thrusters which are needed to be simulated for longer times in a large dimensions and can be addressed by our upgraded scalable PIC simulations.

II. Excitation and propagation of electron electrostatic solitary waves

Initial process of the charge neutralization of an ion beam by electron injection is investigated using a two-dimensional electrostatic Particle-in-Cell code [7]. The simulation results show that electrostatic solitary waves (ESWs) can be robustly generated in the neutralization process and last for long time (for more than 30 μs); and therefore ESW can strongly affect the neutralization process during this initial transient process of ion beam neutralization. The ESWs propagate inside the ion beam and interact with each other.

Figure 1 shows plots of temporal evolutions of potential profile along the x-axis when two ESWs collide. As evident from Fig. 1, two ESWs pass through with each other, with their identity almost preserved, because the simulations clearly show that two ESWs can pass through each other with only small changes in amplitude. When their positions coincide, their potential amplitudes are superimposed (not shown in Fig. 1). Partial exchange of trapped electrons in collisions of two ESWs was observed in the simulations and can explain interaction during collisions of two ESWs and is shown in Fig.2.

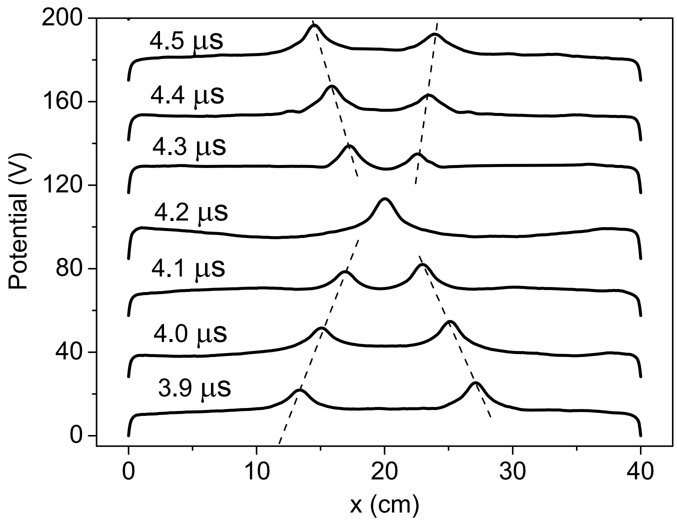

Fig. 1. . Collision of two ESWs passing through each other. Dashed lines represent soliton trajectories on a space-time diagram.

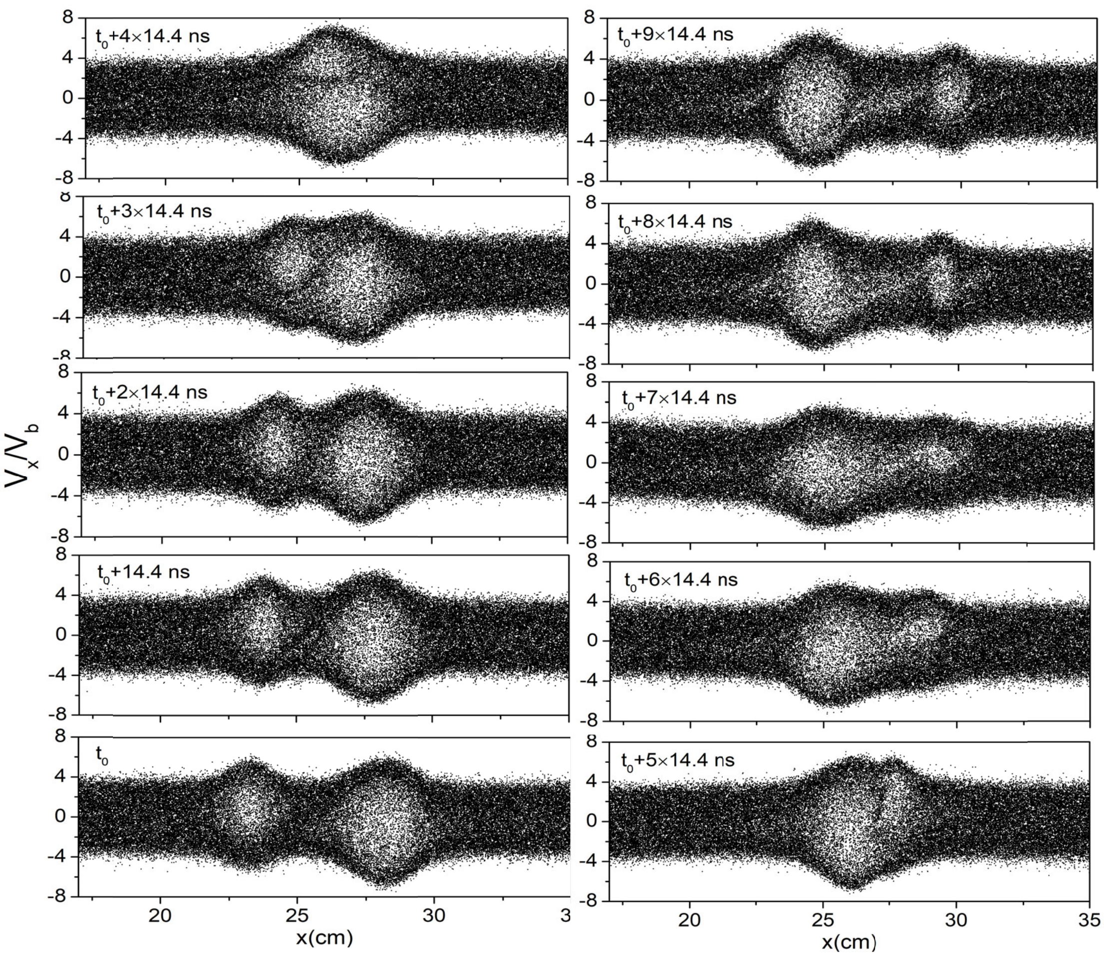

Fig. 2. Evolution of electrons in the x-v_x phase space when two ESWs passing through each other for conditions of Fig.1 [7].

The excitation of ESW was also observed in simulations of ion thrusters[10].

III. Excitation and propagation of ion electrostatic solitary waves

If the electron mean velocity is high compared to ion thermal velocity, a strong ion acoustic turbulence is typically excited. Simulations were run using the PPPL-modified LSP code; modifications included incorporation of the latest version of the Portable Extensible Toolkit for Scientific Computation (PETSc) [11-13] for improved performance and scalability. Poisson's equation was inverted via the SuperLU [14], LU factorization package accessed via the PETSc interface.

The model for ion acoustic turbulence is based off of that described in Ref. [15]. A uniform plasma with 1 eV electrons is initialized with density 10^{11} cm^{-3} over a one-dimensional periodic domain 6.4 cm in length. The system is driven by a 5 V/cm electric field and allowed to evolve in 1D-3V phase space up to 25 microseconds. The Debye length, electron plasma frequency, and electron Courant condition are suitably resolve, each cell maintains approximately 200 particle-per-cell for each species. Simulations are completed in approximately 50 hours running on 32 cores on PPPL's Dawson cluster.

Figure 3 shows ion phase space and excitation of ion accousting turbulence where two ion ESW are clearly seen in the center of simulations. These solitons appear and disappear in turbulence, but seem to be a robust feature of the strong ion acoustic turbulence.

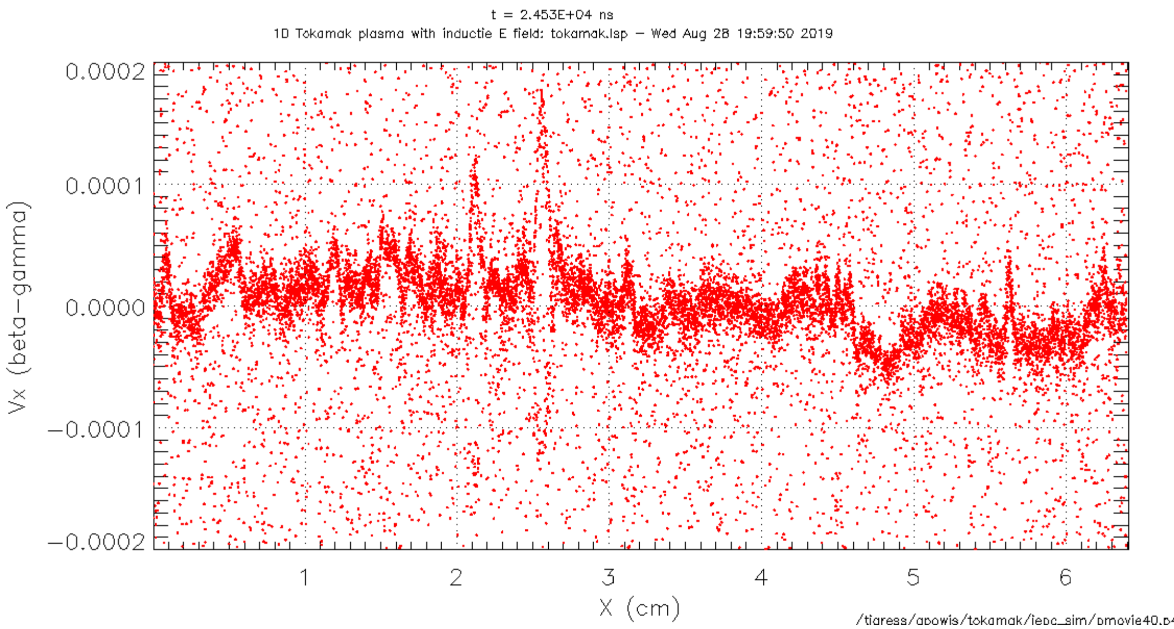

Fig.3 Evolution of ion in the x-v_x phase space. Two solitons are clearly visible in between x=2 cm and x=3cm.

Ion beams propagating through a plasma with a bounded wall may also induce ion sound instabilities. Fluid based linear model [16] showed the ion flow induced ion sound instability (ISI) in a finite length system takes place in the limit of $v_{beam} < c_s$, where v_{beam} is the beam velocity and c_s is the Bohm velocity. The model also identified the ISI main features, e.g., growth rate, real frequency and ISI criteria in the linear phase. The nonlinear and kinetic effects which were not captured in the fluid model are the main scope of the present work. Here, we study the ion beam induced ISI in a finite length system by means of 1D3V particle-in-cell simulations. The 1D simulation domain is bounded by two opposite walls with the separation 1cm. The ion beam is continuously injected from the right wall and the ions are absorbed at the left wall. Both walls are grounded, where approaching electrons are specularly reflected to ensure the "electron background". The figures below show the spatial and temporal evolution of electric field and its spectrum in k space by the PIC simulations when $v_{beam} = 0.8c_s$. Our preliminary simulations demonstrated the ISI phenomena and the instability mode (k=4) is also found consistent with the fluid model in this specific case.

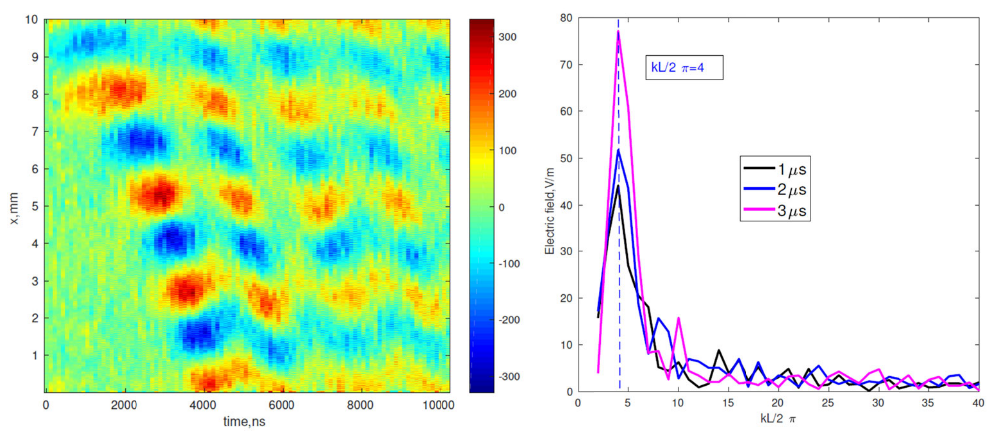

Figure 4. Left: spatial and temporal evolution of electric field. Right: electric field spectrum in k space

IV. The electron cyclotron drift instability (ECDI) in Hall thrusters: effects of the simulation box size and higher number of particles in cell on resulting anomalous transport

For studies of the electron cyclotron drift instability (ECDI) in Hall thrusters we investigated effects of the simulation box size and higher number of particles in cell on resulting anomalous transport [8]. It is found that the instability develops as a sequence of the cyclotron modes demonstrating non-quasineutral large amplitude ion density fluctuations at short wavelengths. The intense long wavelength mode with distinct variations along the magnetic field was identified as the modified two-stream instability leading to strong parallel heating of electrons [8]. We also observed nontrivial effect of longer simulation box on transport due to excitation of the long wavelength structures in azimuthal direction (not excited in short box simulation) and nonlinear wave-wave interaction.

V. Validation and Verification procedures for discharge modeling

For codes to be predictive, several necessary steps have to be performed:

1) Develop minimum complexity self-consistent mathematical model that describes the effects to be predicted

2) Develop numerical codes and check these codes for bugs by benchmarking with other codes, and with analytical or manufacturing solutions, to test convergence

3) Assemble a reliable set of atomistic physics and plasma-surface interaction data required for modelling

4) Perform validation tests by comparing simulation results with available or dedicated experiments capable of exploring a wide range of parameters to test the assumptions and simplifications of the model. The comparisons must be sufficiently comprehensive, see examples and discussion in Refs. [17,18], in order to avoid the bias which may occur when "measurements data and modelling results agree if they are performed in the same Lab," and since a narrow set of measurements data can be matched by variation of adjustable parameters available in the models.

These rigorous procedures are only now being used in electric propulsion community and needs to further employed, see further discussion in Ref.[19].

VI. Conclusion

Electron and ion solitons seem to be ubiquitous feature of collisionless plasma and are relevant to electric propulsion. The Validation and Verification rigorous procedures are only now being used in electric propulsion community and needs to further employed, see further discussion in Ref.[19].

Acknowledgments

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