3D Particle-in-Cell Simulations of Electric Propulsion Ion Beam Neutralization

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Abstract: **Ion beam neutralization during operation of electric propulsion devices requires current coupling between ions and electrons emitted from the neutralizer. The current and often charge density equalization during neutralization is practically accomplished, but the exact process has not been adequately simulated due to the wide range of conditions. In order to resolve the role of electrons in the beam neutralization process, full particle-in-cell (PIC) simulations are carried out using a high-fidelity electrostatic particle-in-cell code (EUPIC). A series of EUPIC simulations of ion beam neutralization is performed, with various configurations and parameters, ranging from fast ions to mesothermal ions in ideal 1D configuration. Results show the current coupling process of both fast and mesothermal ion beams in an idealized 1D configuration.**

Nomenclature

d	=	neutralization distance
v_{di}	=	ion drift velocity
v_{te}	=	electron thermal velocity
λ_D	=	Debye length

I. Introduction

Ion beam neutralization during operation of electric propulsion devices requires both current and charge density matching of the ion beam using emitted electrons. This current coupling is easily accomplished in practice, yet the exact process has not been adequately described. Proper modeling of current coupling and neutralization will enable

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development of low-current neutralizers and optimization of neutralizers for micro-propulsion devices and clusters of thrusters. Explanation of the beam coupling mechanism also has bearing on space instrument calibration, electrodynamic tethers, and ionospheric research.

A dense ion beam requires space charge neutralization to avoid a potential barrier that can divert or reflect the beam. The spacecraft on which the thruster operates needs current neutrality to avoid unwanted charging. In the context of collisionless plasma theory, achieving both current and charge neutrality with the same source of electrons appears to be nearly impossible owing mostly to the large difference in mass between electrons and the ions. However, neutralization is achieved by electrons from thermionic and hollow cathode sources, which do not necessarily provide electrons at such low energies. Since real systems quite easily achieve 'beam coupling', this suggests that a strong mechanism exists for binding the electrons to the ion beam.

In this paper we extend our previous work [1-3] and consider a broader view of ion beam neutralization processes. We first consider an idealized 1D configuration following a theoretical ion beam model [4] and carry out fully-kinetic particle-in-cell (PIC) simulations in an effort to resolve full current coupling of ion beams. Section II introduces the 1D neutralization model and describes the PIC simulation setup. Section II presents the results for both fast and mesothermal ion beams. Finally, conclusions are given in Section IV along with discussion about future work.

II. 1D Neutralization Model and Simulation Setup

A. Idealized 1D Neutralization Model

The idealized 1D ion beam neutralization model is illustrated in Figure 1. In this model, ions and electrons are injected from the same plane into vacuum. Space charge and current neutralization is assumed to take place at a distance d downstream of the injection plane. When neutralization is achieved, $n_e = n_i$ and $v_{di} = v_{de}$, so that $J_i = J_e$. A detailed description of the idealized 1D ion beam neutralization model can be found in Ref. [4]. Figure 2 plots the normalized neutralization distance (d/λ_D) for Xe, H, and D ion as a function of the dimensionless ratio of Beam Kinetic Energy (KE_i) over Electron Thermal Energy (kT_e). It shows that 1D ion beams can span a wide range of KE_i/kT_e therefore resulting in the non-dimensional neutralization distance ranging from < 1 to as large as ~ 25. For example, for some fast ion beams where the ion drift velocity (v_{di}) is larger than electron thermal velocity (v_{te}), the non-dimensional neutralization distance can be as large as 25. On the other hand, for some mesothermal ion beams where $v_{di} < v_{te}$

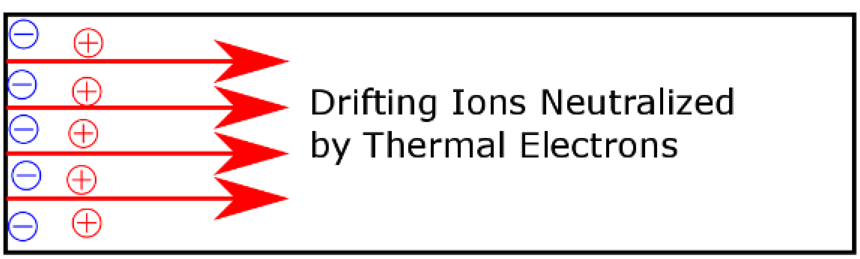


Figure 1. An idealized 1D ion beam neutralization model.

(typical for electric propulsion devices), the non-dimensional neutralization distance are mostly predicted to be within a few Debye lengths downstream of the beam injection plane.

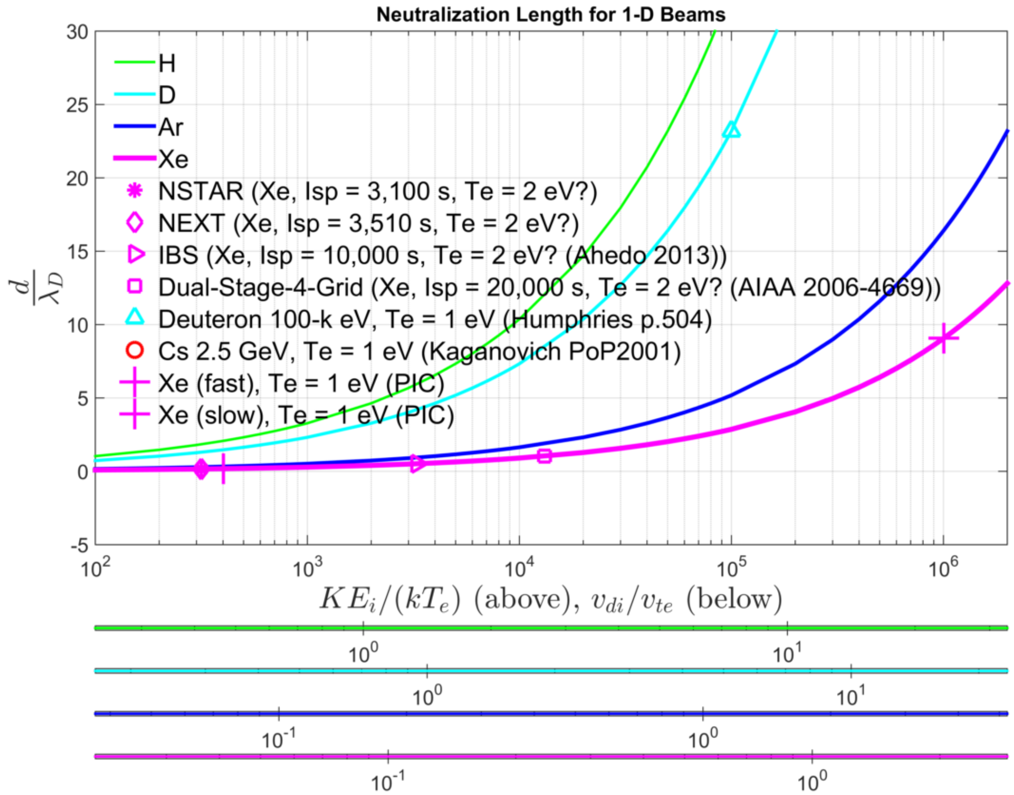


Figure 2. Normalized neutralization distance as a function of non-dimensional beam kinetic energy using the idealized 1D ion beam neutralization model [4]. The horizontal axes are colored for different ion species. The question mark "?" of electron temperatures indicate estimations.

B. Simulation Setup

In this paper, we perform a series of PIC simulations using an electrostatic unstructured particle-in-cell (EUPIC) code

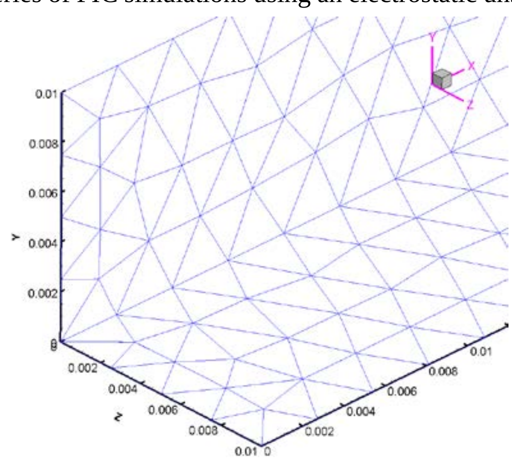


Figure 3. 1-D simulation mesh. The simulation domain is a long rectangular box (10 × 10 × 2000 mm).

[1-3]. PIC codes have been used widely for beam neutralization simulations and require control of numerical heating

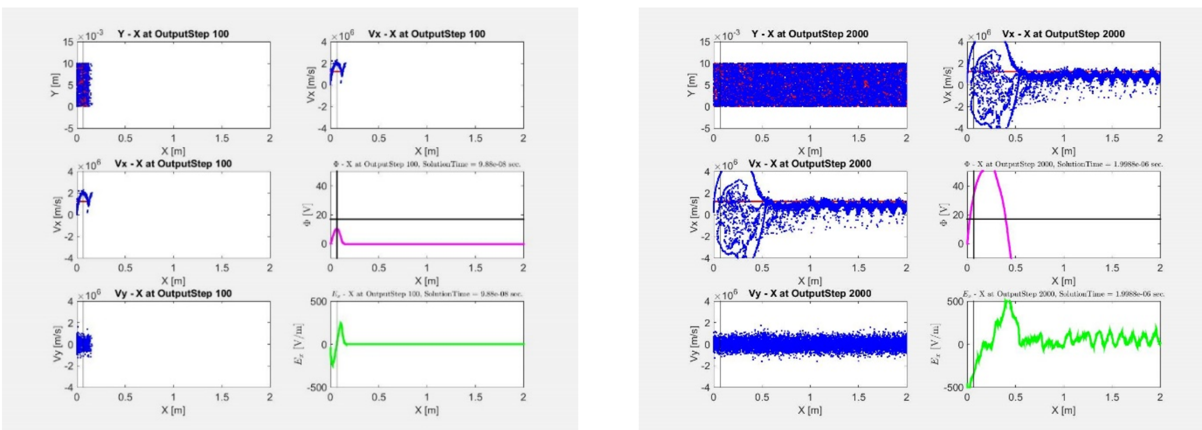
that is inherent in PIC codes. To validate the EUPIC and develop a comprehensive background on 1D beam neutralization by co-emitted electrons a series of simulations are performed. Ion beams of Xe with non-dimensional kinetic energy $\frac{KE_i}{kT_e} \sim 1 \times 10^3 - 1 \times 10^6$ are considered, while the corresponding velocity ratio is $\frac{v_{di}}{v_{te}} \sim 0.1 - 1.0$, covering the range expected in electric propulsion devices as well as high-energy beams. The simulation domain is a long rectangular tube ($10 \times 10 \times 2000$ mm) where the ion beam drifts along *x*-direction. A typical simulation mesh is shown in Figure 3. Beam ions are injected at X_{min} boundary and thermal, stationary electrons are accelerated under the self-consistent electrical field generated by the beam front. Reflection particle boundary conditions are set at side walls. Particles hitting the X_{max} boundary are removed from the simulation. The potential at X_{min} boundary is fixed to be zero while zero-Neumann E field boundary conditions are applied to side walls as well as X_{max} boundary.

III. Results and Discussion

In this section, we present PIC simulation results for both fast ions and mesothermal ions.

A. Fast Ions

The ion beam drift velocity considered for "fast ions" case is set to be 1.212×10^6 m/s. The electron temperature is set to be 1 eV. Figure 4 shows the phase space and E field profiles of the fast ion beam neutralization process at different time steps. It is observed that, for a fast ion beam ($v_{di} > v_{te}$), the neutralization process obtained from the PIC simulation matches the idealized 1D neutralization model quite well with regard to the non-dimensional neutralization distance. As the ion beam propagates downstream, the electrons eventually gain a bulk drift velocity same as the ion drift velocity (v_{di}) and thus current coupling is achieved.



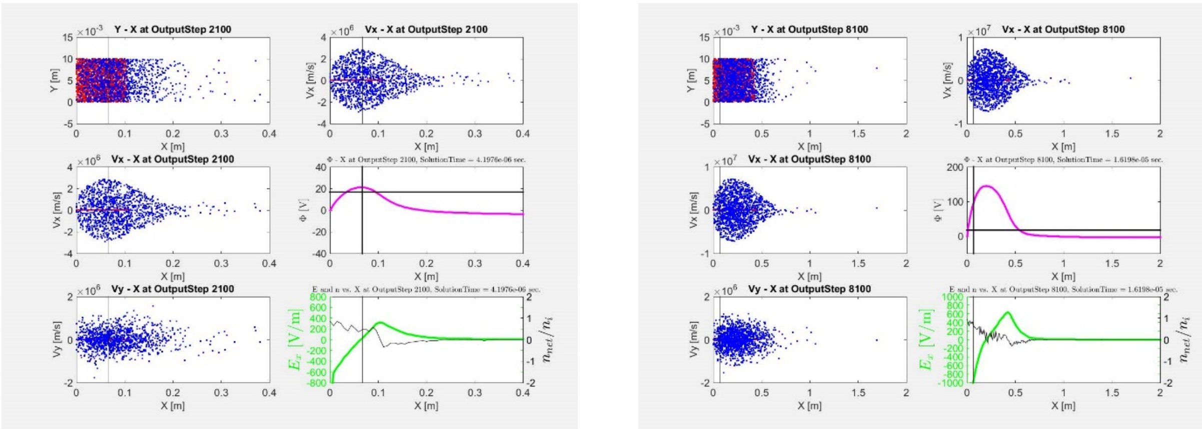
a) Phase space and E field at an early stage of the fast ion beam neutralization. The vertical line in the x-axis indicates the non-dimensional neutralization distance predicted by the idealized 1D model. At this stage, the PIC simulation results match the idealized 1D model well.

b) Phase space and E field at a later stage of the fast ion beam neutralization. The vertical line in the x-axis indicates the non-dimensional neutralization distance predicted by the idealized 1D model. At this stage, the ion beam has achieved current and density neutralization.

Figure 4. Phase space and electric field of 1D ion beam neutralization for fast ions.

B. Mesothermal Ions

The ion beam drift velocity considered for "mesothermal ions" case is set to be 0.024×10^6 m/s. The electron temperature is set to be 1 eV, same as the "fast ions" case. Figure 5 shows the phase space and E field profiles of the mesothermal ion beam neutralization process. The kinetics of electrons are quite different from that of the "fast ions" case in a way that in a mesothermal ion beam, ion drift velocity is smaller than electron thermal velocity ($v_{di} < v_{te}$). The potential well caused by the ion beam front at the early stage does not trap enough electrons to neutralize the ion beam. Therefore, the idealized 1D ion beam neutralization model described in Ref. [5] is not sufficient to resolve the neutralization process of the mesothermal ion beams emitted by typical electric propulsion devices.



a) Phase space and E field at an early stage of the mesothermal ion beam neutralization. The vertical line in the x-axis indicates the non-dimensional neutralization distance predicted by the idealized 1D model.

b) Phase space and E field at a later stage of the mesothermal ion beam neutralization. The vertical line in the x-axis indicates the non-dimensional neutralization distance predicted by the idealized 1D model.

Figure 5. Phase space and electric field of 1D ion beam neutralization for mesothermal ions. The kinetics of electrons do not match the idealized 1D model because of the smaller ion drift velocity compared to the electron thermal velocity.

IV. Summary and Conclusions

In order to resolve the role of electrons in the beam neutralization process, fully-kinetic particle-in-cell simulations are carried out using a high-fidelity electrostatic particle-in-cell code (EUPIC). A series of EUPIC simulations of ion beam neutralization is performed for both fast ions ($v_{di} > v_{te}$) and mesothermal ions ($v_{di} < v_{te}$) in an idealized 1D configuration. Results show the current coupling process of both fast and mesothermal ion beams. The numerical simulation successfully resolved the current and density neutralization process of 1D fast ion beams, which is in good agreement with the theoretical 1D beam neutralization model. For mesothermal ions, the numerical simulation does not yield a good agreement with the theoretical 1D model. Further investigations will study effects of background plasmas as well as 2-D and 3-D effects.

Acknowledgments

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