

Kinetic Simulations of Ion Beam Neutralization

IEPC-2009-263

*Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009*

Joseph Wang¹
University of Southern California, Los Angeles, CA 90089-1192, USA

Hideyuki Usui²
Kobe University, Kobe, Japan

Abstract: This paper presents a kinetic simulation study of ion beam neutralization and plasma beam propagation, and discusses the physics of electron-ion coupling and the resulting propagation of a neutralized mesothermal plasma. It is shown that beam neutralization and propagation are two closely coupled processes. The initial expansion of thermal electrons over cold beam ions establishes ion-acoustic-like beam front propagation. Subsequently, the emitted electrons are trapped in the region between the forward propagating beam front and the emitting source. Electron-ion coupling is achieved through the interactions between the trapped electrons and the potential well, and is not through plasma instability as previous studies suggested.

I. Introduction

Ion beam emission/neutralization is one of the most fundamental problems in electric propulsion. It is well known that, in order to transmit a current exceeding the space charge limit from spacecraft to the ambient, the beam must be adequately neutralized or the transmission would be blocked by virtual anode formation in the beam¹ and spacecraft charging. Hence, the operation of an electric thruster or any other large current ion emitting source from spacecraft requires a neutralizer to neutralize the ion beam. In such systems, the ions are typically emitted as a cold beam while the electrons are typically emitted as stationary thermal electrons from the neutralizer. The emission is such that $v_{te} \gg v_{beam} \gg v_{ti}$, where v_{te} , v_{beam} , v_{ti} are the electron thermal velocity, beam drifting velocity, and ion thermal velocity, respectively, and the electron current emitted equals the ion current emitted. One notes that the plasma emitted is strongly non-neutral near the source regardless of the neutralizer location or the emitting surface area. Even for a hypothetical situation where the electrons and ions were emitted from exactly the same location and same surface area, the initial beam would still be strongly non-neutral due to the difference in electron and ion emitting velocity.

The ion beam neutralization process not only is an interesting physics problem but also has important practical implications. For instance, such knowledge is important in the neutralization design for electric thruster clusters. It is obviously also of critical importance in any modeling studies involving plasma emission. Ion beam neutralization is one of the first problems studied during electric propulsion development. Although ion beam neutralization is readily achieved in experiments, the understanding of the underlying physical process remains at a rather primitive level. No theoretical or simulation models have convincingly explained the detailed neutralization mechanism.

Earlier theoretical and simulations models have considered the neutralization of infinitely large uniform ion beam²⁻⁶. More recent models have considered a more realistic setting for finite size ion beam emission⁷⁻⁹. These previous studies suggest that wave-particle interaction and plasma instability may be the driving neutralization mechanism. However, no conclusions have been reached. Part of the reason for the lack of a good understanding of the neutralization process is because particle simulation of beam neutralization is an extremely challenge problem

¹ Astronautical Engineering Division, josephjw@usc.edu.

² Department of Computer Science and Systems Engineering, h-usui@port.kobe-u.ac.jp

due to computational constraints. This is because, in order to simulate the physics correctly, such simulations must be carried out using the realistic ion to electron mass ratio so the correct mesothermal velocity order for ions and electrons, $v_{te} \gg v_{beam} \gg v_{ti}$ can be maintained. Additionally one must also use a very large simulation domain in order to minimize the effects of the simulation domain boundary.

This paper presents a fully kinetic simulation of ion beam neutralization and plasma beam propagation. The focus is on the physics of electron-ion coupling and the resulting propagation of the mesothermal plasma. Section 2 presents the simulation model. Section 3 discusses the simulation result. Section 4 contains a summary and conclusions.

II. Simulation Model

The ion beam neutralization process involves the following aspects: initial mixing of electrons and ions, electron-ion coupling, and beam propagation. The initial electron-ion mixing, to a large extent, is determined by device design and hence, the mixing process varies for different systems. In this paper, we will focus on the electron-ion coupling and beam propagation aspects.

The problem is studied using full particle PIC simulation. In this model, both the electrons and ions are modeled as macro-particles. The particle dynamics, space charge, and electric field are solved self-consistently. In order to reduce the computation, the 3-D PIC code is applied to a 2-D configuration. The simulation setup is shown in Fig. 1. We consider that the electrons and ions are emitted from the same surface area but with different velocity distribution functions. At every time step, Macro-particles representing the ions are emitted into the simulation domain as a drifting Maxwellian distribution and those representing the electrons as a stationary Maxwellian distribution. In order to maintain the realistic relative velocity ratio between the beam velocity, and electron and ion thermal velocities in the simulation, the simulations are performed using a realistic mass ratio of $m_i/m_e=1836$. Comparing to v_{te} , v_{beam} and v_{ti} are $v_{beam}=0.1 v_{te}$ and $v_{ti}=0.0023 v_{te}$, respectively. These relative values are similar to typical ion thruster parameters.

The emitted electron and ion currents are kept the same. For a cold beam ions and thermal electrons, the electron and ion current density at the emitting surface are $J_{e0}=n_{e0} < v_{te} >$ and $J_{i0}=n_{i0}v_{beam}$, respectively, where n_{e0} and n_{i0} denote the electron and ion density outside the emitting surface, respectively. For the v_{te} and v_{beam} considered here, $n_{e0} \sim 0.2n_{i0}$. Hence, if the electrons and ions were uncoupled, such an emission would lead to a very non-neutral beam, as illustrated in Figure 2.

In the simulation, the cell size equals the Debye length calculated using n_{i0} and the electron temperature T_e at the emitting surface. We consider a spacecraft with size 50×50 . The beam emission width is $R_T=20$. The simulation domain is taken to be 600×400 , or $30R_T \times 20R_T$. The potential at spacecraft body is fixed and while the potential at domain boundary is floating. The number of macro-particles near the emitting source is $\sim 850/\text{cell}$ for each population and the total number of marco-particles used at end of run is typically around 7 million. Simulations were run using a time step resolution of $dt\omega_{pe} \sim 0.1$, where dt and ω_{pe} denote the time step and the electron plasma frequency, respectively.

III. Results and Discussions

Typical simulation results are presented in Figs. 3 through 8. Fig.3 shows potential contour at $t\omega_{pe}=1600$ ($t\omega_{pi}=37.3$ where ω_{pi} denotes the ion plasma frequency). Fig.4 shows electron and ion positions, electron density contour, ion density contour, and total charge density contour at $t\omega_{pe}=1600$ ($t\omega_{pi}=37.3$). These results show that, while the beam is strongly non-neutral near the emitting source, the electron-ion coupling occurs immediately at the downstream of the emitting source and a quasi-neutral plasma beam quickly forms. The thermal electrons follow the motion of the cold beam ions, and the electron density closely matches the ion density inside the beam. For this particular case, the potential inside the beam at the downstream of the beam exit surface is only a few T_e .

To investigate the process of electron and ion coupling, Figs. 5 through 7 show the time evolution of the phase plots, potential profiles, and electron and ion density profiles along the beam direction. In these plots, we compare the snapshots taken at $t\omega_{pe}=40$ ($t\omega_{pi}=0.93$) with that at $t\omega_{pe}=1600$ ($t\omega_{pi}=37.3$). The initial electron expansion along the beam direction follows the same physical process studied in 1-D expansion of a mesothermal plasma into vacuum. It is well understood that such expansion establishes an ion-acoustic like beam front propagation. As the electron thermal velocity is much larger than the ion beam velocity, the region behind the beam front will have a slightly positive potential with respect to the ambient. Hence, the region between the beam source and the beam front gradually traps the electrons. It is the interaction between the trapped electrons and the potential well that leads to electron-ion coupling and beam neutralization. Further frequency and wave number spectrum analysis (not shown here) also show that no beam plasma instabilities were present. We also performed the linear dispersion analysis

using the plasma parameters such as the electron and ion velocities and densities observed in the potential well. However, the obtained growth rate of the beam instability is too small to grow. Therefore, in the current case, we find that ion beam neutralization is not through plasma micro-instability, as previous studies suggested. As the beam front propagates forward, the electrons and ions develop a similar density profile along the beam direction, as shown in Fig. 8. Once the quasi-neutral beam is established, an expansion wave is generated outside the beam (Fig. 4c and 4d). The expansion in the transverse direction is similar to that associated with the self-similar expansion of a mesothermal plasma into vacuum.

IV. Summary and Conclusions

In summary, we have developed a full particle PIC simulation model to simulate the ion beam neutralization process. We find that beam neutralization and propagation are two closely coupled processes. The initial expansion of thermal electrons over cold beam ions establishes ion-acoustic-like beam front propagation. Subsequently, the emitted electrons are trapped in the region between the forward propagating beam front and the emitting source. Electron-ion coupling is achieved through the interactions between the trapped electrons and the potential well along the beam direction. Beam neutralization is not through plasma instabilities as previous studies suggested. Self-similar expansion of ion acoustic waves similar to that associated with plasma expansion into vacuum also occurs in the transverse direction outside the beam. Because of electron trapping in the beam direction and the interactions between the trapped electrons and the electric field, the electron distribution is highly non-Maxwellian along the beam direction. Hence, the commonly used Boltzmann assumption for electron density in spacecraft plasma interaction models in general is not valid for interactions concerning plasma beam emission.

Acknowledgments

The authors acknowledge computational support from Yong Cao and Coling Chang. JW acknowledges the hospitality and financial support of Kyoto University where a part of this work was carried out.

References

- ¹Wang, J. and Lai, S., Virtual Anode in Ion Beam Emissions in Space: Numerical Simulations, *J. Spacecraft Rockets*, 34(6), 1997, p829-836.
- ²Buneman, O. and Kooyers, G., Computer Simulation of the Electron Mixing Mechanism in Ion Propulsion, *AIAA J.* 1(11), 1963, p2525-2528.
- ³Wadhwa, R., Buneman, O., Brauch, D., Two-Dimensional Computer Experiments on Ion Beam Neutralization, *AIAA J.*, 3(6), 1965, p1076-1081.
- ⁴Dunn, D. and Ho, T., Longitudinal Instabilities in an Electrostatic Propulsion Beam with Injected Current Neutrality, *AIAA Preprint* 63041, 1963.
- ⁵Derfler, H., Nonexistence of Quiescent Plasma States in Ion Propulsion, *Physics of Fluids* 7(10), 1964, p1625-1637.
- ⁶Buneman, O., Maintenance of Equilibrium by Instabilities, *J. Nucl. Energy C*, V2, 1961, p119-134.
- ⁷Wheelock, A., Cooke, D., and Gatsonis, N., Ion Beam Neutralization Processes for Electric Micropropulsion Applications, *AIAA* 2003-5148, 2003.
- ⁸Brieda, L., and Wang, J., Modeling Ion Thruster Beam Neutralization Using a Fully Kinetic ES-PIC Code, *AIAA* 2005-4045, 2005.
- ⁹Cao, Y. and Wang, J., Modeling Ion Beam Neutralization, *IEPC* 2007-241, 2007.

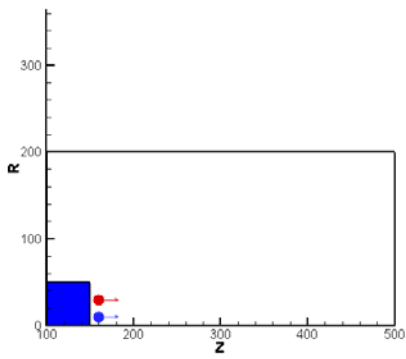


Figure 1. Simulation setup.

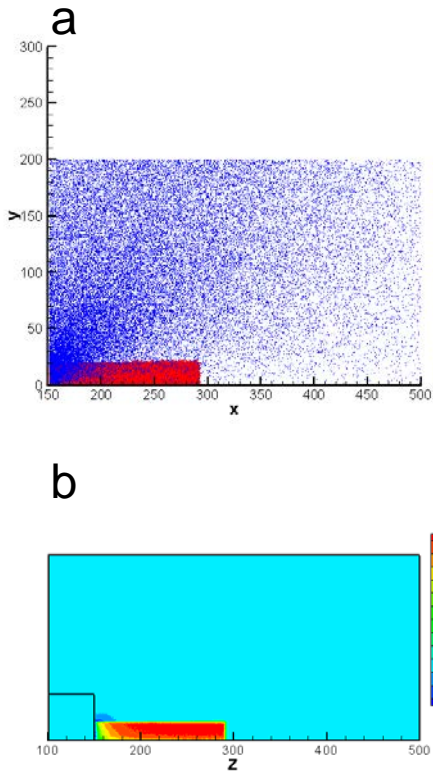


Figure 2. Illustration of a hypothetical non-neutral beam generated by the emission of cold beam ions and thermal electrons. a) electron (blue) and ion (red) positions; b) total charge density contour.

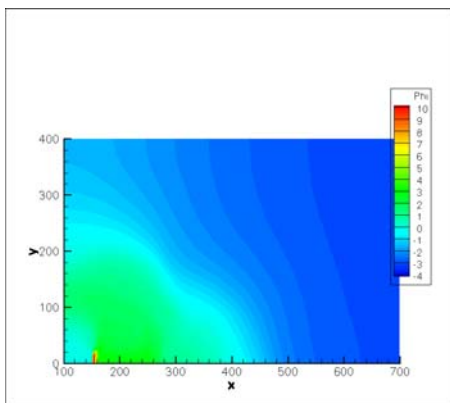


Figure 3. Simulation results: potential contour at $t\omega_{pe}=1600$ ($t\omega_{pi}=37.3$).

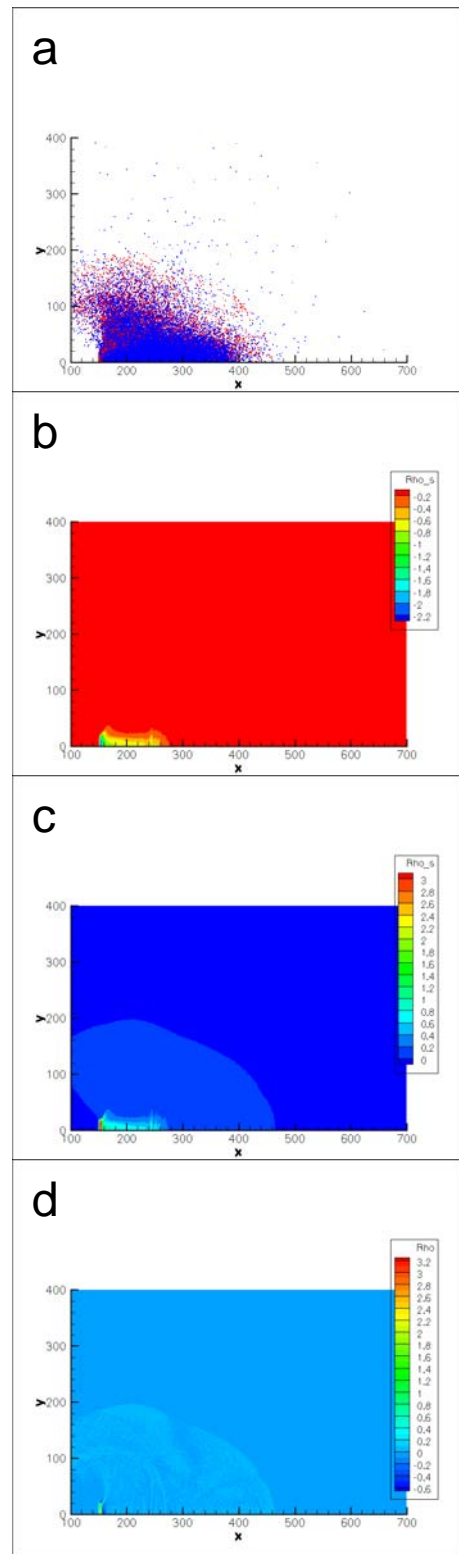


Figure 4. Simulation results: a) electron (blue) and ion (red) positions. b) electron density contour; c) ion density contour; d) total charge density contour at $t\omega_{pe}=1600$ ($t\omega_{pi}=37.3$).

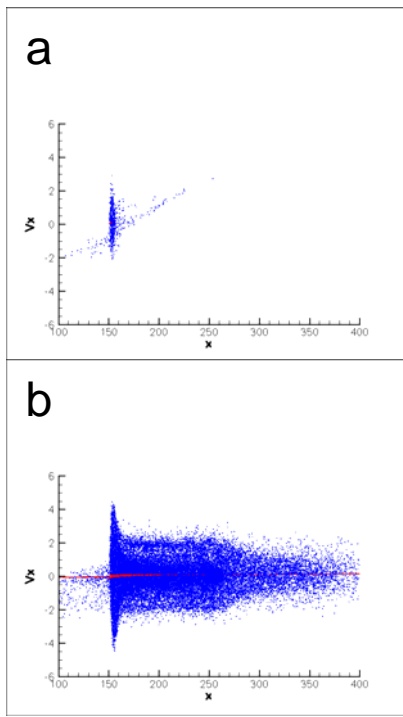


Figure 5. Phase plots for electrons (blue) and ions (red). a) $\omega_{pe}=40$ ($\omega_{pi}=0.93$) b) $\omega_{pe}=1600$ ($\omega_{pi}=37.3$).

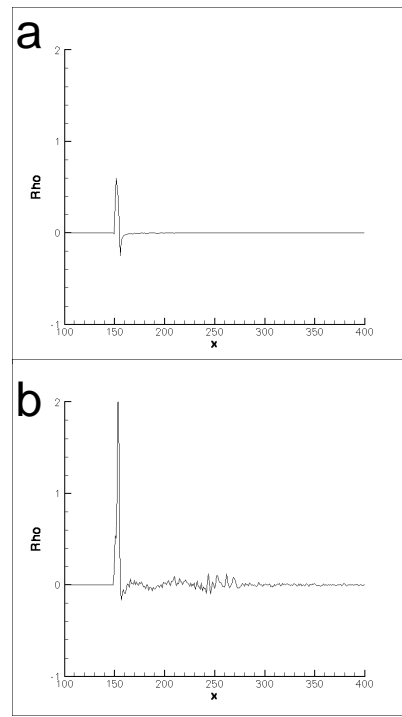


Figure 7. Total charge density profile along the center axis a) $\omega_{pe}=40$ ($\omega_{pi}=0.93$) b) $\omega_{pe}=1600$ ($\omega_{pi}=37.3$).

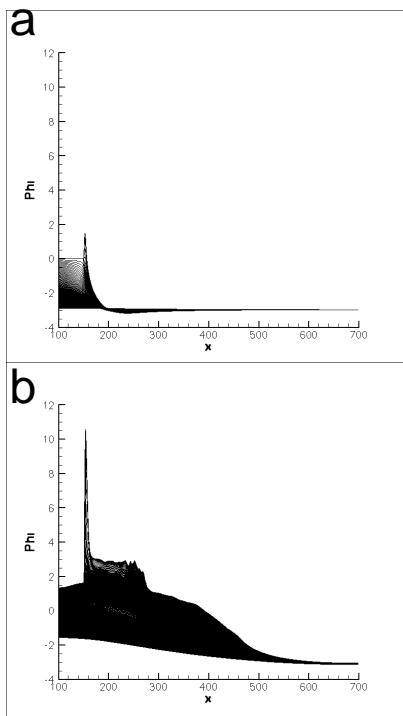


Figure 6. Potential profiles along the beam direction a) $\omega_{pe}=40$ ($\omega_{pi}=0.93$) b) $\omega_{pe}=1600$ ($\omega_{pi}=37.3$).

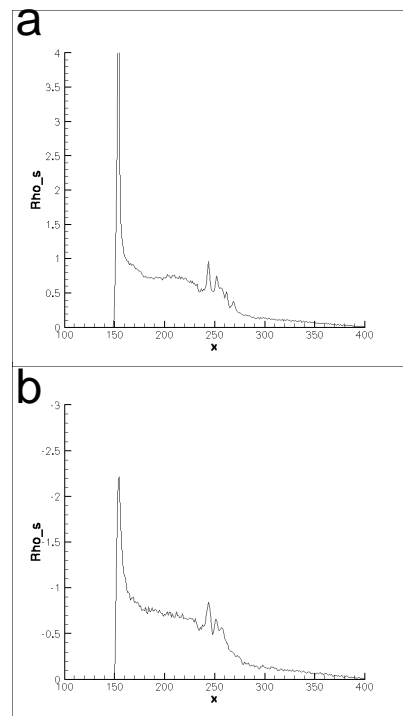


Figure 8. Ion density profile (a) and electron density profile (b) along the center axis at $\omega_{pe}=1600$ ($\omega_{pi}=37.3$).