Lattice-Boltzmann Models of Ion Thrusters

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Lattice-Boltzmann Method (LBM) & Ion Thrusters

- Complement Discrete Simulation Monte-Carlo (DSMC) models for faster computation of critical ion thruster parameters
- Use LBM to model plasma flow in thruster
- Compare results with experimental data and DSMC predictions
- Identify plasma flow characteristics that lead to thruster component erosion; e.g., grids
Outline

- **Ion thrusters (see Gallimore, 2004)**
  - Basic physics of operation
  - Issues of interest: lifetime/erosion
- Why try LBM?
- LBM & Ion thrusters
- Some results
- Summary, conclusion & future work
Ion thrusters are the most efficient EP devices at converting input power to thrust and are used both as primary propulsion and for station-keeping on commercial and scientific spacecraft.

Key issues include grid erosion and thrust density limitations from space-charge effects.
Ion Thrusters Basics

- Electrons are emitted from discharge cathode assembly (DCA)
- DCA electrons (Primary) are accelerated by local sheath to high voltage (>15 eV)
- Primary electrons create ions via impact ionization with neutrals
- Ionization process starts with one Primary and one neutral - results in 2 Maxwellian electrons and one ion
- Ions are attracted to ion optics (Screen grid) via electric field
- Ions are accelerated through optics (Screen & Accel grids) - ion beam neutralized by neutralizer cathode
- Accel grid negative to prevent electron backstreaming
- Note: While Maxwellian electrons outnumber Primaries 10:1, the latter account for most of the ionization in the discharge chamber.
Modern Ion Thrusters

Solar Electric Propulsion — NASA’s Evolutionary Xenon Thruster (NEXT) [5-10 yr. deployment time]
- NEXT is the follow-on to NSTAR used on DS1 and slated for DAWN (2006 launch)
- NEXT represents a 4x improvement in thrust and power and a 25% increase in Isp (from 3280 to 4100 s) over NSTAR at half the specific mass (from 2.6 to 1.2 kg/kW)

Nuclear Electric Propulsion — NASA’s Nuclear Space Initiative [10-15 yr. deployment time]
Electric Propulsion Proposals in NASA’s 2002 “In-Space Propulsion Technologies” NASA Research Announcement (NRA) for ultra-high-performance engines (Isp > 6,000 s)
Ion Thruster Basics

Ion Beam
Non-Collisional Ion Trajectory

Charge Exchange Collision

Low PERVEANCE MARGIN - High Ne but Low j

High PERVEANCE MARGIN - Low Ne but High j

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Ion Thruster Basics

- Screen Grid ~1170 V
- Anode ~1200 V
- Neutralization Plane ~0 V
- Equipotentials (simulation)
- Potential
- Axial Position (mm)
- Under-focus
- Over-focus

- Ion "Birth" Potential
- Accel Grid -300 V
- $X_a$
- $2X_a$
Typical Ion Engine Parameters

- Within a few cm of grid, typical ion thruster & plasma parameters are:
  \[ n_{Xe^+} \sim 10^{12} - 10^{10} \text{ cm}^{-3}, \ n_e \sim 10^{12} - 10^{10} \text{ cm}^{-3} \gg n_{Xe} \gg n_{Xe^{++}} \ldots \]
- \( V_+ \sim 1075 \text{ V} \) at screen grid
- \( V_- \sim -150 \text{ V} \) at accelerator grid
- Grid separation \( \sim 1 \text{ mm} \)
- Screen grid opening diameter \( \sim 2 \text{ mm} \)
- Accelerator grid opening diameter \( \sim 1 \text{ mm} \)
Assumptions of Applicability of LB

- Note local $Kn$: $Kn = \frac{\lambda}{L} = \frac{RT}{\sqrt{2} \pi d^2 N_A p L}$
- $Kn \sim O(0.1)$ around optics
- Ion veloc. distrib. Laser-induced Fluorescence Velocimetry of Xe II in the 30-cm NSTAR-type Ion Engine Plume, Smith and Gallimore (AIAA-2004-3963)
- Maxwellian radial $f(v)$
LBM EP Model

- The model assumes coupling of the velocity distribution function with the electrostatics:
  \[ \frac{\partial f}{\partial t} + c \cdot \nabla_r f - \frac{q}{m} \nabla_r \phi \cdot \nabla_c f = Q(f, f) \]
  \[ \varepsilon_0 \nabla^2 \phi = e \int f d^3 c \]

- Assume linear collision if close to the continuum limit so that \( Q = -\nu_r (f - f^{(eq)}) \)

- Adequate for near equilibrium plasma, simple charge exchange (CEX) collisions or even assume “\( Q=0 \)” for collisionless, electrically-driven plasma
Computational Procedure

Initialization: $f_{\alpha} = f_{\alpha}^{(eq)} = \rho w_{\alpha} \left[ 1 + \frac{3}{c^2} e_{\alpha} \cdot u + \frac{9}{2c^4} (e_{\alpha} \cdot u)^2 - \frac{3}{2c^2} u \cdot u \right]$

Collision: $\tilde{f}_{\alpha}^{(t)} = f_{\alpha}^{(t)} - \frac{1}{\tau} \left[ f_{\alpha}^{(t)} - f_{\alpha}^{(t, eq)} \right] + g_{\alpha}$

Electrostatics: $\varepsilon_0 \nabla^2 \phi = e \sum_{\alpha=0}^N f_{\alpha}^{(t+\delta t)}$

Sources: $f_{\alpha} = f_{\alpha}^{(eq)} = \rho w_{\alpha} \left[ 1 + \frac{3}{c^2} e_{\alpha} \cdot u + \frac{9}{2c^4} (e_{\alpha} \cdot u)^2 - \frac{3}{2c^2} u \cdot u \right]$

$t = t + dt$

Streaming: $f_{\alpha}^{(t+\delta t)}(x_i + e_i \delta t, t + \delta t) = f_{\alpha}^{(t)}(x_i, t)$

Calculate physical variables

$\rho^{(t+\delta t)} = \sum_{\alpha=0}^N f_{\alpha}^{(t+\delta t)}$

$\rho^{(t+\delta t)} u^{(t+\delta t)} = \sum_{\alpha=0}^N e_{\alpha} f_{\alpha}^{(t+\delta t)}$
Axi-symmetric Cylindrical Coordinates

- In accordance w/thruster geometry
- Use work of Yu, Girimaji & Yu (2004) where cyl. coord. effects are incorporated via source terms in LBE to satisfy macro-level cyl. coord. eqs. (NS)

\[ g_\alpha = w_\alpha s + \frac{3}{c^2} w_\alpha e_\alpha \cdot a \]

where,

\[ s = -\frac{u_r}{r}, \quad a_z = -\frac{v}{r} \frac{\partial u_z}{\partial r} + \frac{q}{m} \frac{\partial \phi}{\partial z} \frac{\partial f}{\partial v_z}, \quad a_r = \frac{v}{r} \left( \frac{\partial u_r}{\partial r} - \frac{u_r}{r} \right) + \frac{q}{m} \frac{\partial \phi}{\partial r} \frac{\partial f}{\partial v_r} \]
Results

- Compare general trends: non-dimensional
- Compare specific cases
LBM Ion Thruster Exhaust Stream

Unitless ion #density contours; matches Crawford (2001)
LBM Ion Thruster Exhaust Stream

Ion velocity field
LBM Ion Thruster Exhaust Stream

Electrostatic potential
LBM Models of Ion Thruster Optics

- To look at grid erosion, we want to zoom in on a grid segment with 2D/axi-symmetric models as below

Electrostatic potential contours from modeling a slit between grids

Electrostatic potential contours from Duchemin (2001)
LBM Ion Thruster Optics

Electrostatic potential
LBM Models of Ion Thruster Optics

- Zoom in on a optics segment with 2D/axisymmetric models as below

Electrostatic potential contours from modeling a slit between grids

Electrostatic potential contours from Duchemin (2001)
LBM Models of Ion Thruster Optics

Electrostatic potential between grids

Electrostatic potential contours from Gallimore (2004)

Electrostatic potential contours from Duchemin (2001)
LBM Ion Thruster Optics

\[ v_{\text{ion}} : V_{\text{screen}} = 10V, \ V_{\text{accel}} = -10V \]
LBM Models of Ion Thruster Optics

Ion # density; screen grid 10V, accelerator grid -10

Crawford (2001)
LBM Models of Ion Thruster Optics

Ion # density; screen grid 1075V, accelerator grid -180
LBM Models of Ion Thruster Optics

Ion velocity field; screen grid 1075V, accelerator grid -180
Conclusions & Future Work

- LBM does well w/modeling EP
- Next is to try
  - other species
  - variations in collision operator, e.g., pseudo-random collision frequency as used in DSMC
  - Other variations of BE form
Computational Domain

- Screen grid
- Accelerator grid
- Computational Domain

S1, S2, S3, S4, S5
Extrapolation Boundary

 Extrapolation boundary condition has been applied at S1 and S4 in computational domain.

 At S1,
  - $f(1,j,9) = f(2,j,9)$
  - $f(1,j,2) = f(2,j,2)$
  - $f(1,j,6) = f(2,j,6)$

 At S4,
  - $f(NX,j,8) = f(NX-1,j,8)$
  - $f(NX,j,4) = f(NX-1,j,4)$
  - $f(NX,j,7) = f(NX-1,j,7)$
Free stream boundary

- Free stream boundary condition has been applied at S2 and S3 in the computational domain.

- At S2,
  - $f(1,j,9) = 0.0$
  - $f(1,j,2) = 0.0$
  - $f(1,j,6) = 0.0$

- At S3,
  - $f(NX,j,8) = 0.0$
  - $f(NX,j,4) = 0.0$
  - $f(NX,j,7) = 0.0$
Symmetric Boundary

- Symmetric boundary condition has been applied at S5 on the computational domain.

- At S5,
  - \( f(i,1,7) = f(i,2,8) \)
  - \( f(i,1,3) = f(i,2,5) \)
  - \( f(i,1,6) = f(i,2,9) \)