Lattice-Boltzmann Models of Ion Thrusters

Dr. Jacques C. Richard
richard@aero.tamu.edu
And
Prerit Shah
Prerit_aggie@neo.tamu.edu
Texas A & M University
College Station, TX 77845, USA

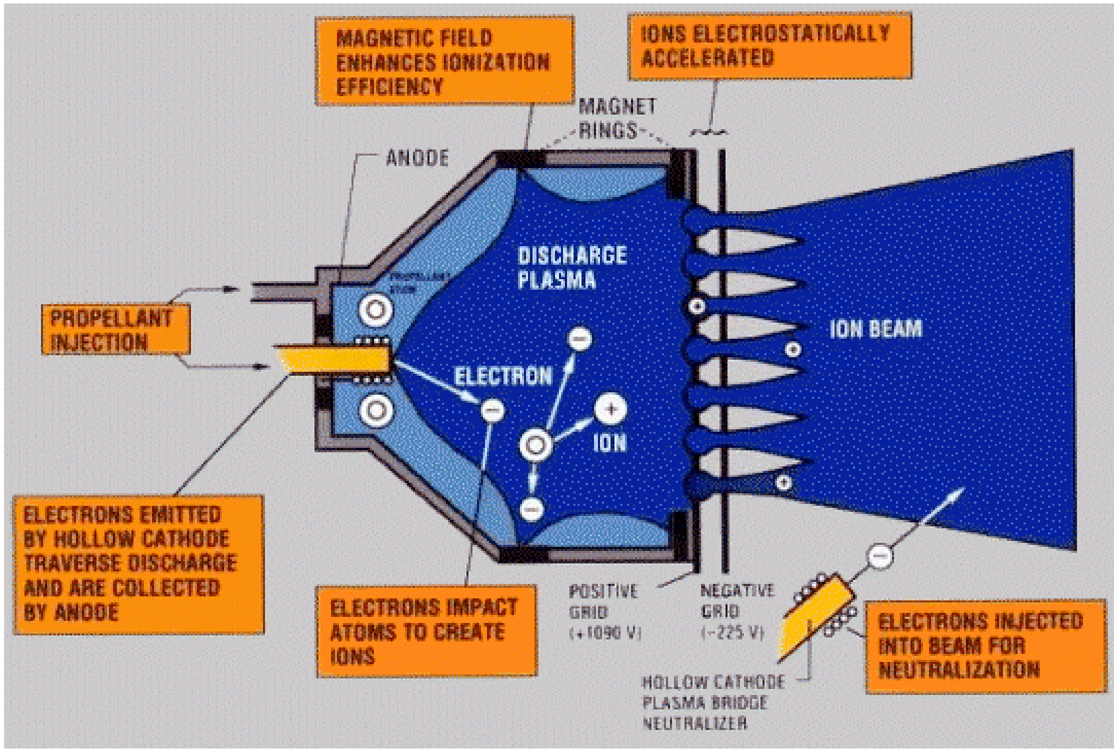
Lattice-Boltzmann Method (LBM) & Ion Thrusters

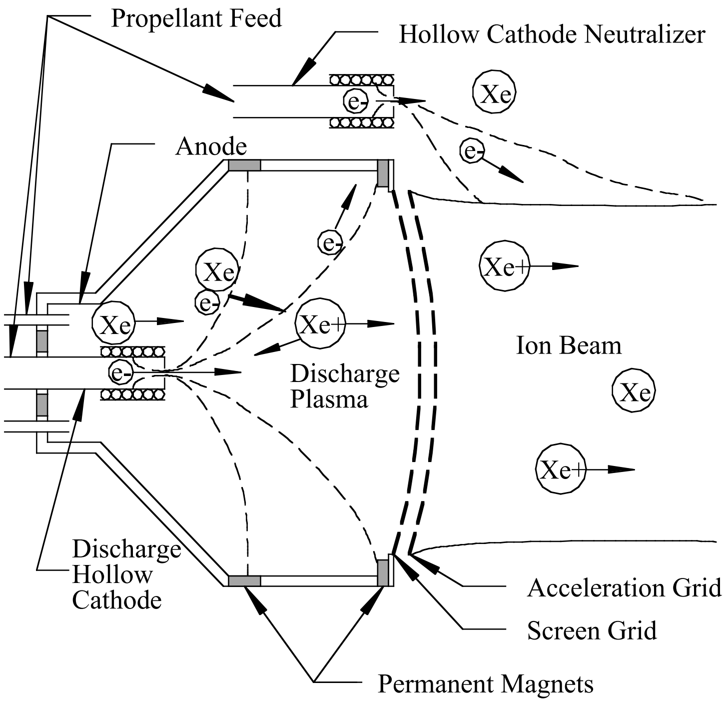
- Complement Discrete Simulation Monte-Carlo (DSMC) models for faster computation of critical ion thruster parameters
- Use LBM to model plasma flow in thruster
- Compare results with experimental data and DSMC predictions
- Identify plasma flow characteristics that lead to thruster component erosion;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

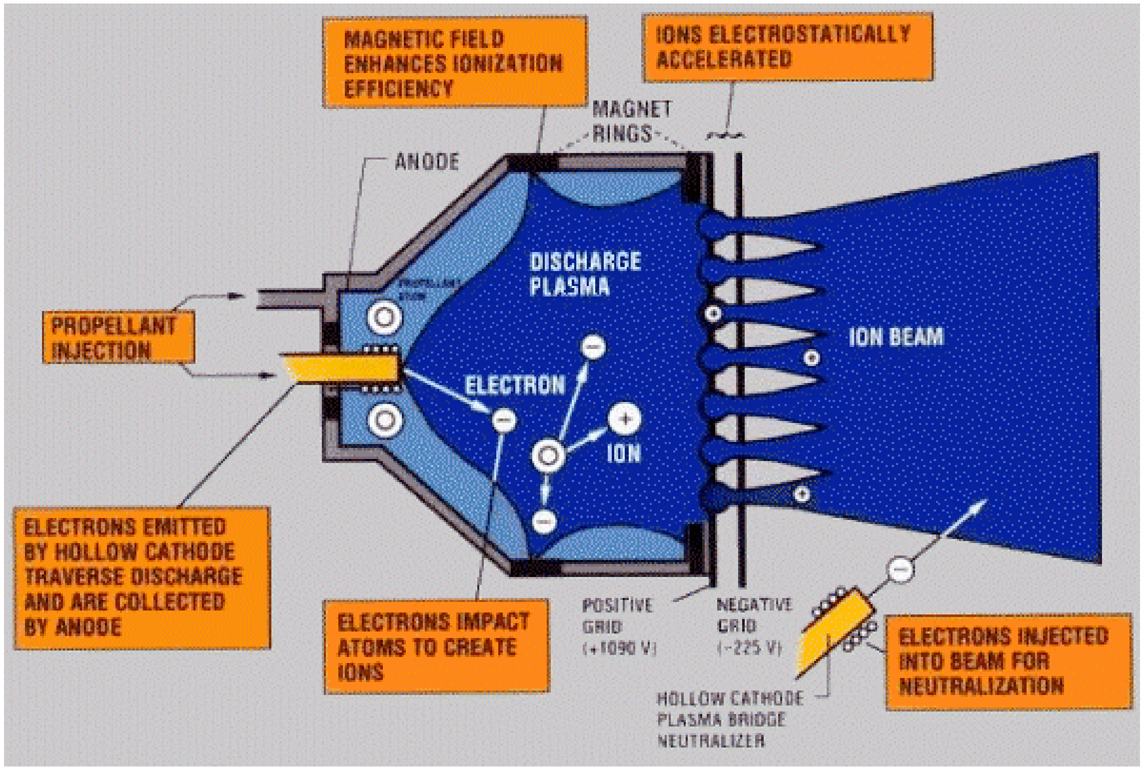
Ion Thrusters





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



Ion thruster concept (Gallimore, 2004)

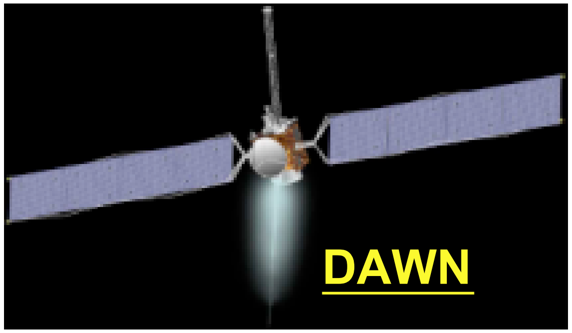
- Electrons are emitted from discharge cathode assembly (DCA)
- DCA electrons (*Primary*) are accelerated by local sheath to high voltage (>15 eV)
- *Primary* electrons create ions via impact ionization with neutrals
- Ionization process starts with one *Primary* and one neutral - results in 2 *Maxwellian* 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]

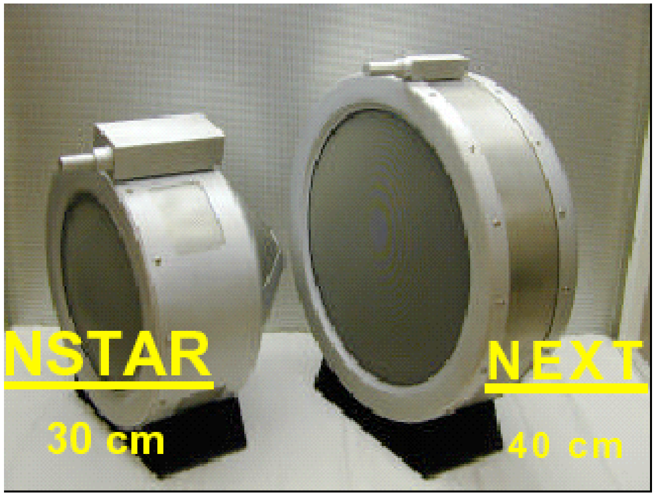
-NEXT is the follow-on to NSTAR used on DS1 and slated for DAWN (2006 launch)

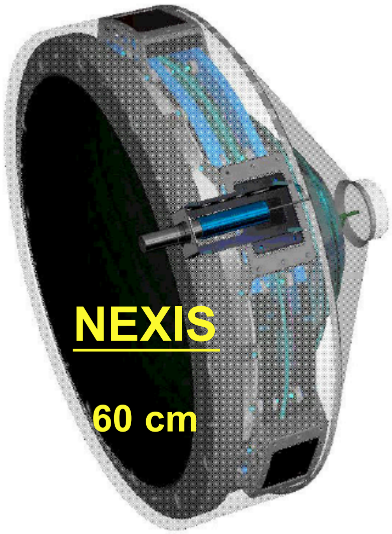
-NEXT represents a 4x improvement in thrust and power and a 25% increase in Isp (from 3280 to 4100 s) over NSTAR at half the specific mass (from 2.6 to 1.2 kg/kW)

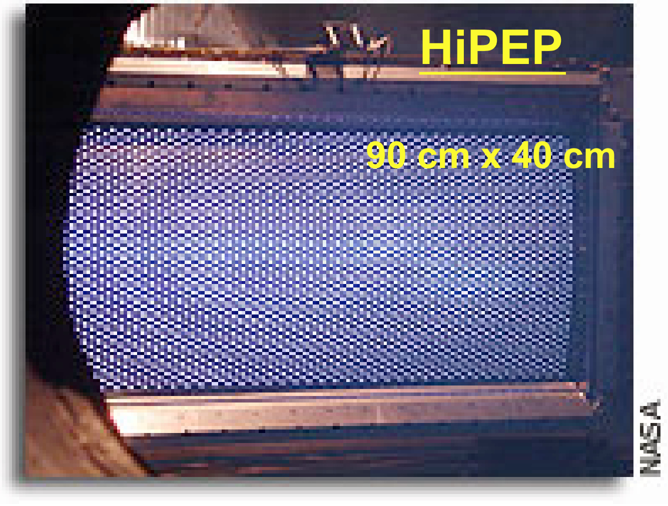


Nuclear Electric Propulsion — NASA's Nuclear Space Initiative [10-15 yr. deployment time]

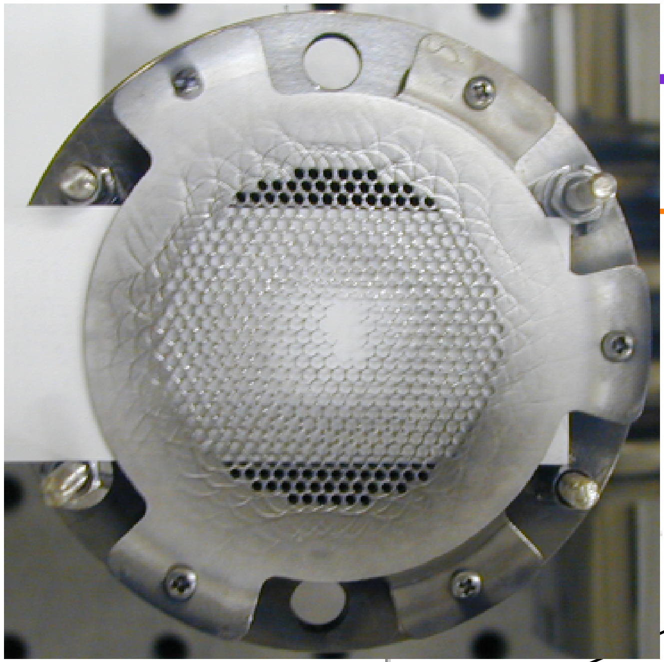
Electric Propulsion Proposals in NASA's 2002 "In-Space Propulsion Technologies" NASA Research Announcement (NRA) for ultra-high-performance engines (Isp > 6,000 s)

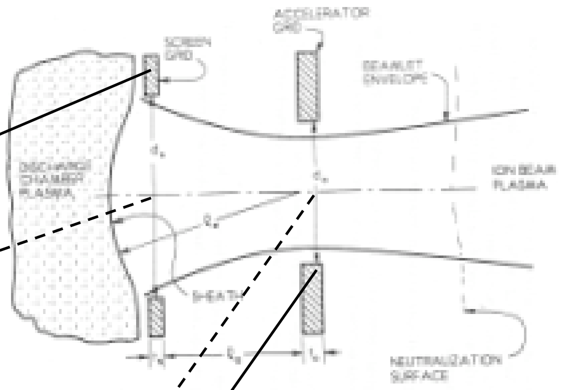


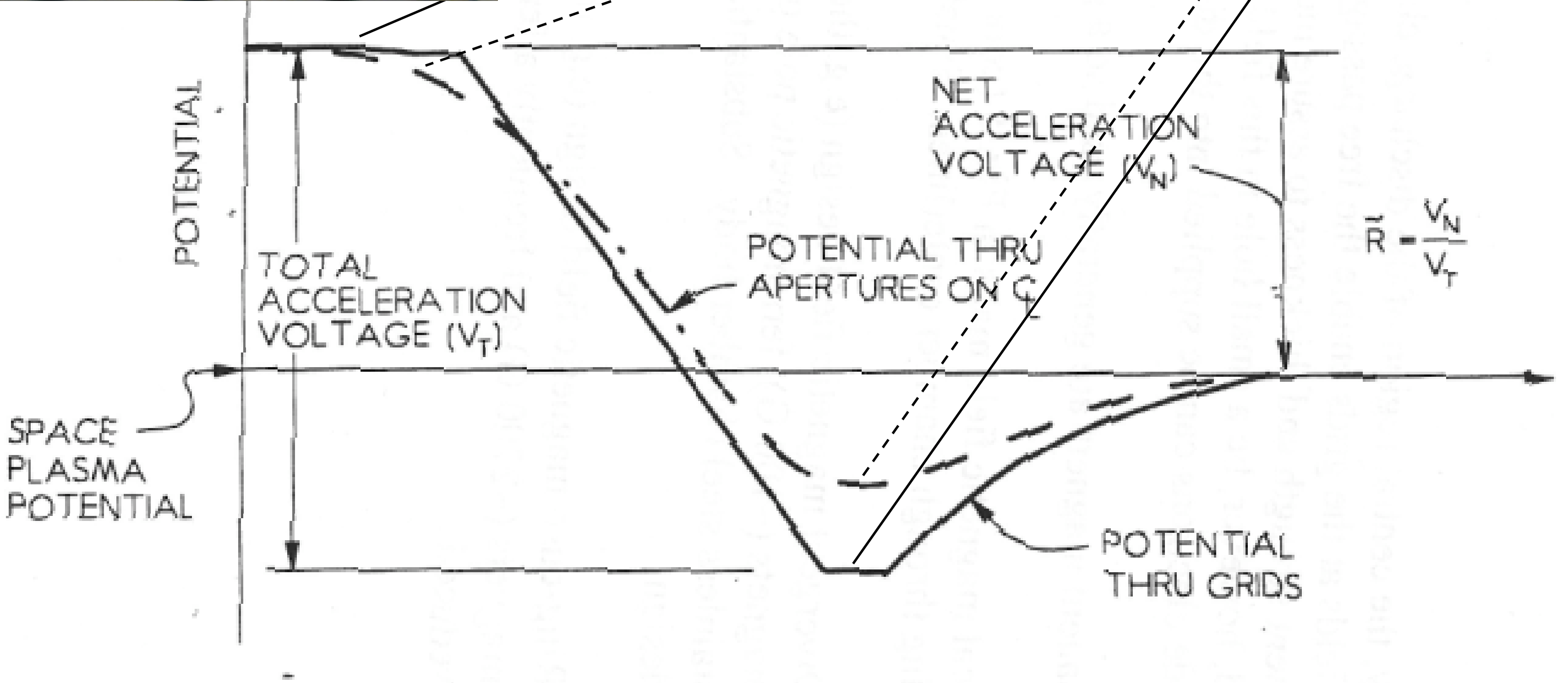




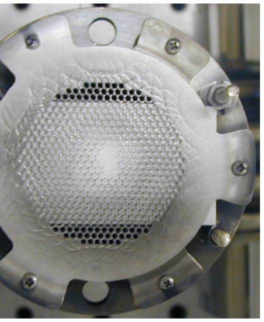
Thruster Basics

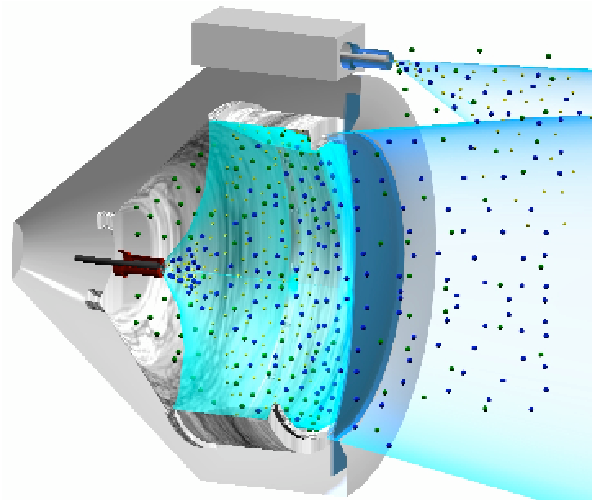


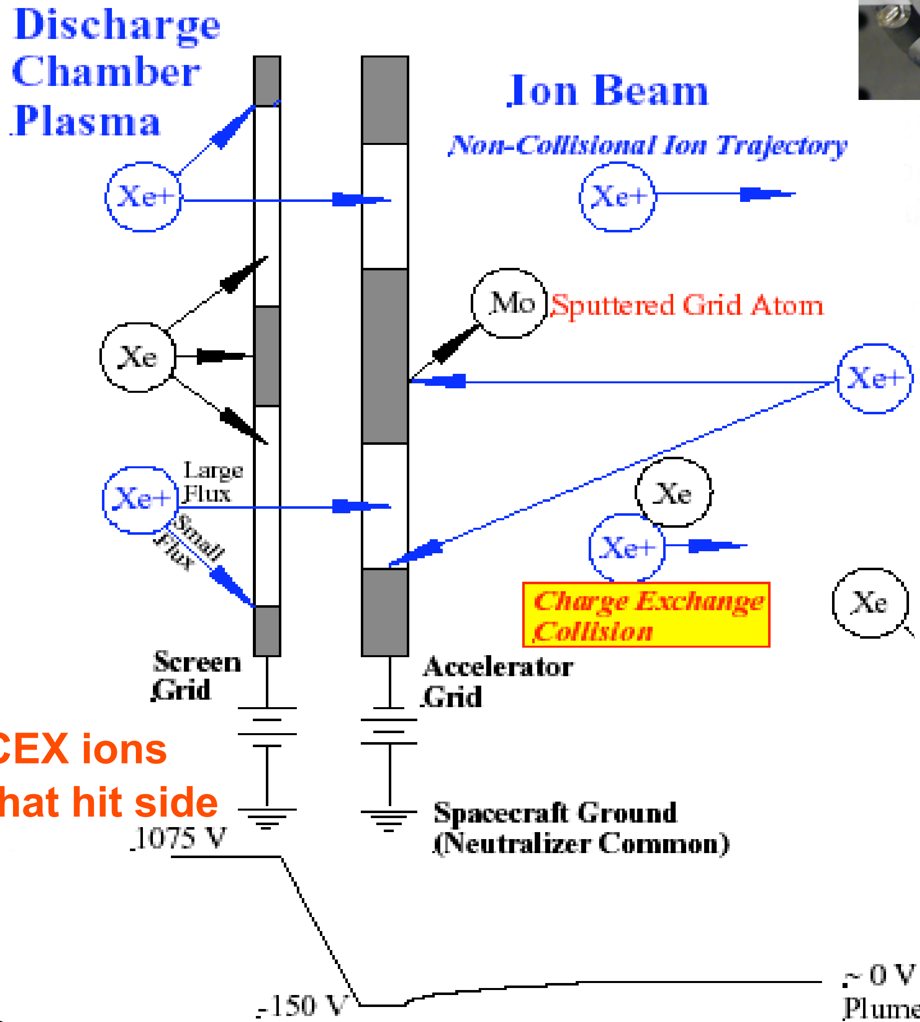


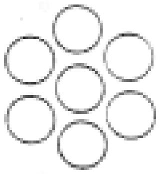


Ion Thruster Basics



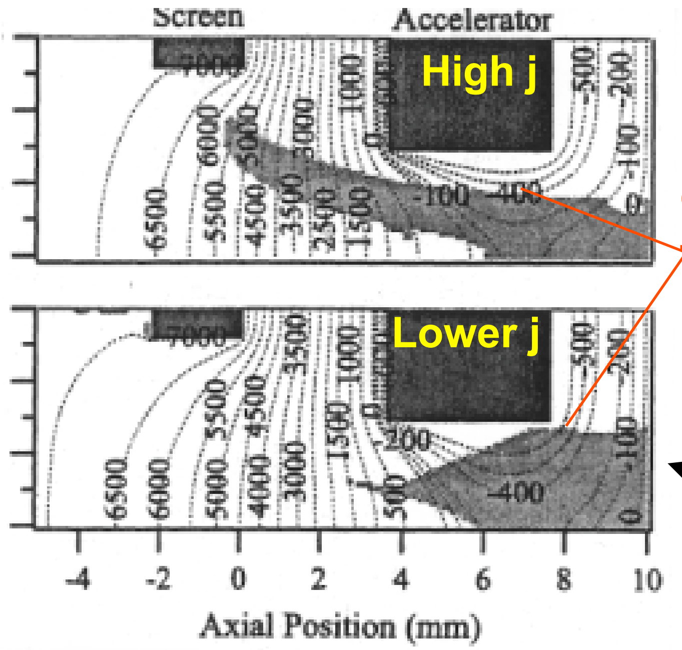






Slow CEX Ion

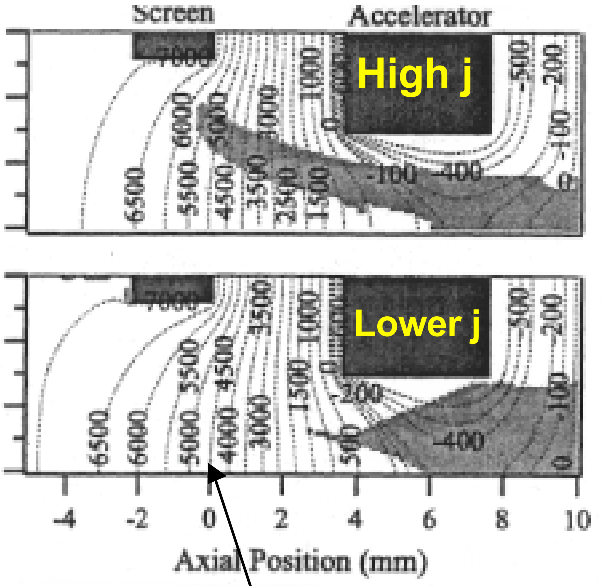
Fast CEX Neutral



CEX ions that hit side

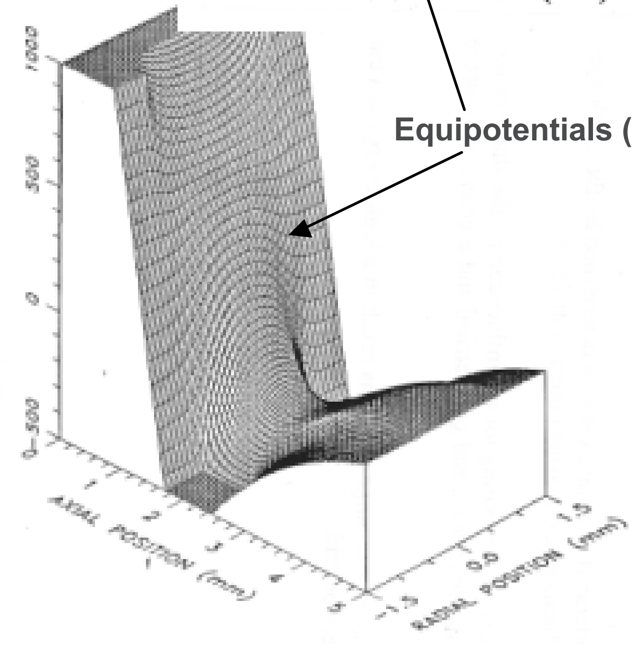
High PERVEANCE MARGIN - Low Ne but High ϕ

Ion Thruster Basics

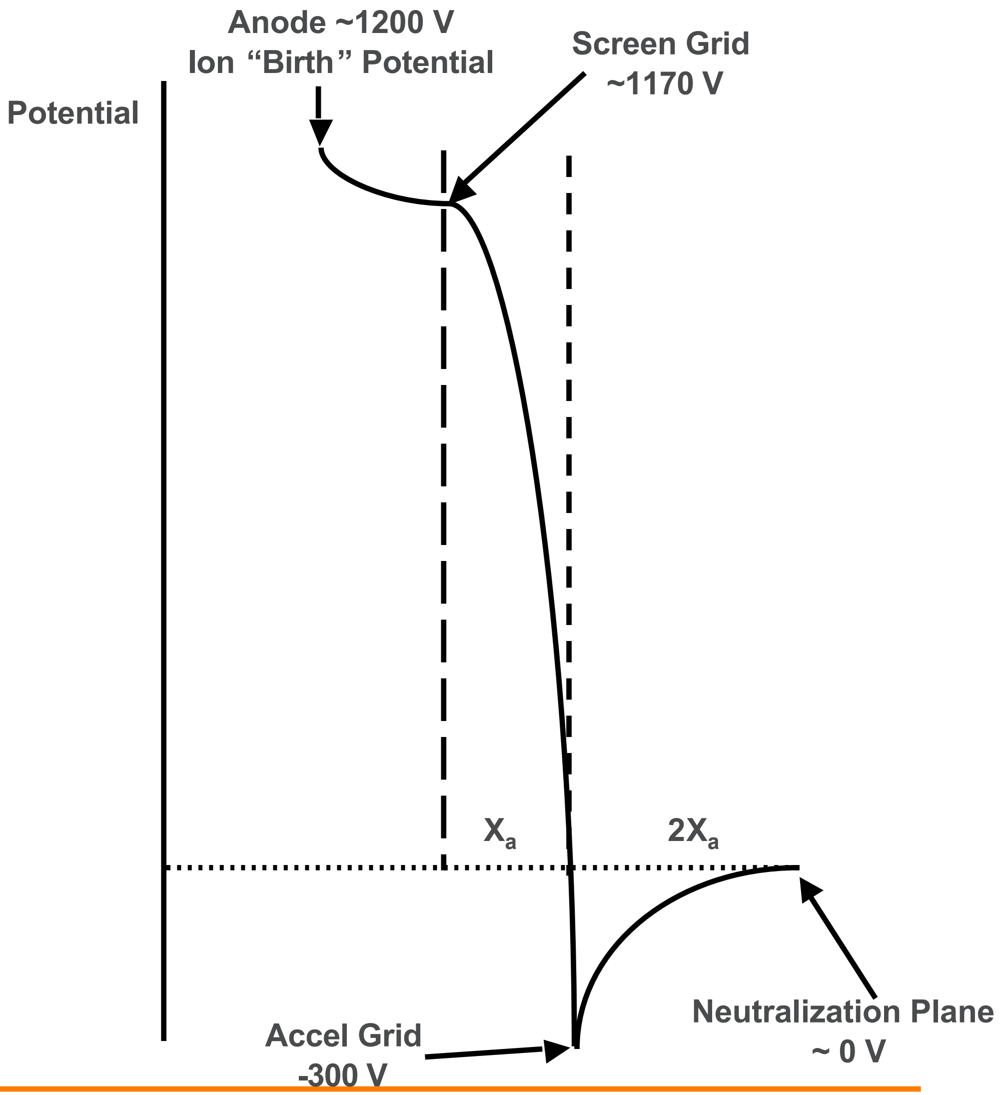


under-focus

over-focus



Equipotentials (simulation)



Potential

Anode ~1200 V
Ion “Birth” Potential

Screen Grid
~1170 V

X_a

$2X_a$

Accel Grid
-300 V

Neutralization Plane
~ 0 V

Typical Ion Engine Parameters

- Within a few cm of grid, typical ion thruster & plasma parameters are:

n_{Xe+}~ 10^{12}-10^{10} cm^{-3} , n_e ~ 10^{12}-10^{10} cm^{-3} >> n_{Xe} >> n_{Xe++} …

- V_+ ~ 1075 V at screen grid
- V_- ~ -150 V at accelerator grid
- Grid separation ~ 1 mm
- Screen grid opening diameter ~ 2 mm
- Accelerator grid opening diameter ~ 1 mm

Assumptions of Applicability of LB

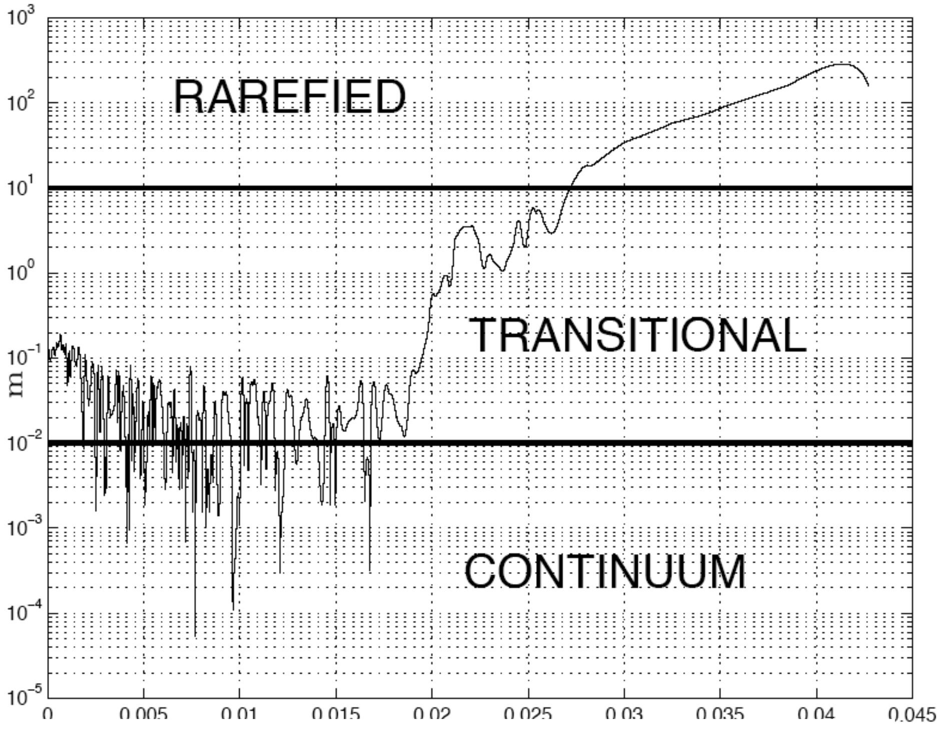
- Note local Kn:

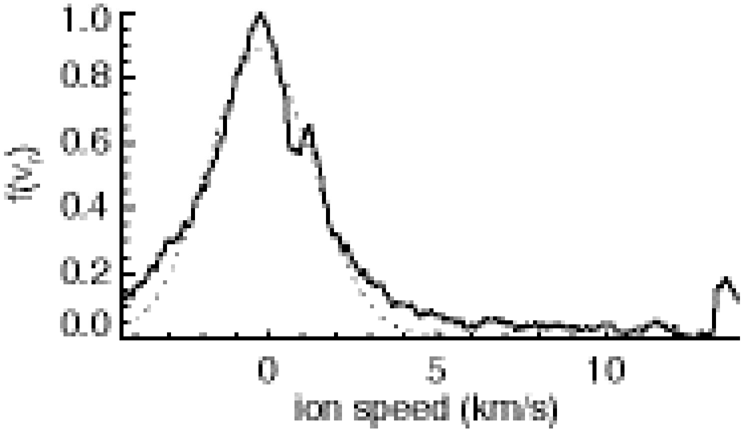
$$Kn = \frac{\lambda}{L} = \frac{RT}{\sqrt{2}\pi d^2 N_A p L}$$

Crawford (2002)

$$L = \frac{\rho}{d\rho / dx}$$

- $Kn \sim O(0.1)$ 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 $f(\mathbf{v})$





LBM EP Model

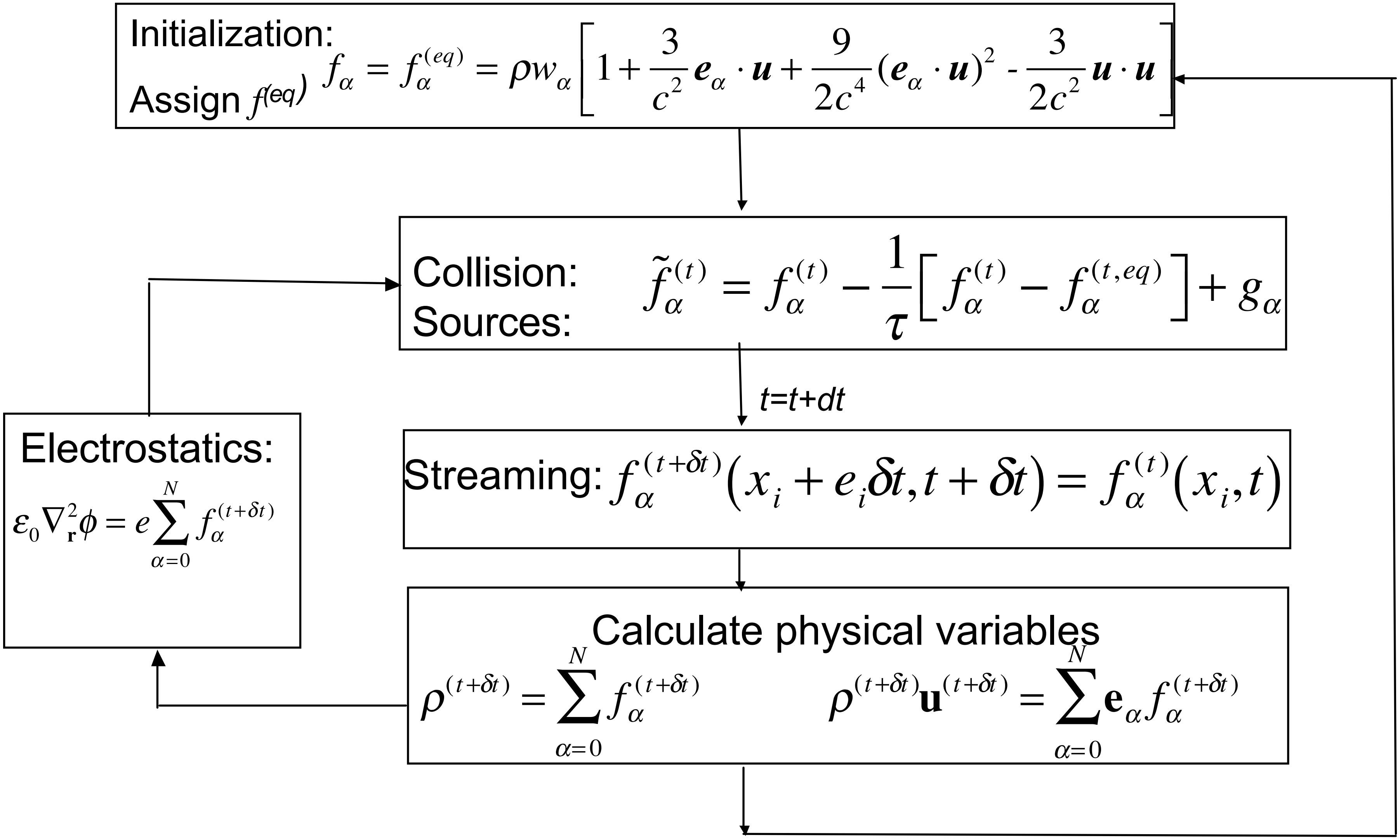
- The model assumes coupling of the velocity distribution function w/the electrostatics

$$\frac{\partial f}{\partial t} + \mathbf{c} \bullet \nabla_{\mathbf{r}} f - \frac{q}{m} \nabla_{\mathbf{r}} \phi \bullet \nabla_{\mathbf{c}} f = Q(f, f)$$

$$\varepsilon_0 \nabla_{\mathbf{r}}^2 \phi = e \int f d^3 \mathbf{c}$$

- 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:

Assign $f^{(eq)}$ $f_\alpha = f_\alpha^{(eq)} = \rho w_\alpha \left[1 + \frac{3}{c^2}\boldsymbol{e}_\alpha \cdot \boldsymbol{u} + \frac{9}{2c^4}(\boldsymbol{e}_\alpha \cdot \boldsymbol{u})^2 - \frac{3}{2c^2}\boldsymbol{u} \cdot \boldsymbol{u}\right]$

Collision:

Sources:

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

t=t+dt

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

Calculate physical variables

$$\rho^{(t+\delta t)} = \sum_{\alpha=0}^{N} f_\alpha^{(t+\delta t)} \qquad \rho^{(t+\delta t)}\mathbf{u}^{(t+\delta t)} = \sum_{\alpha=0}^{N} \mathbf{e}_\alpha f_\alpha^{(t+\delta t)}$$

Electrostatics:

$$\varepsilon_0 \nabla_{\mathbf{r}}^2 \phi = e\sum_{\alpha=0}^{N} f_\alpha^{(t+\delta t)}$$

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)

$$g_\alpha = w_\alpha s + \frac{3}{c^2} w_\alpha \mathbf{e}_\alpha \cdot \mathbf{a}$$

$$where,$$

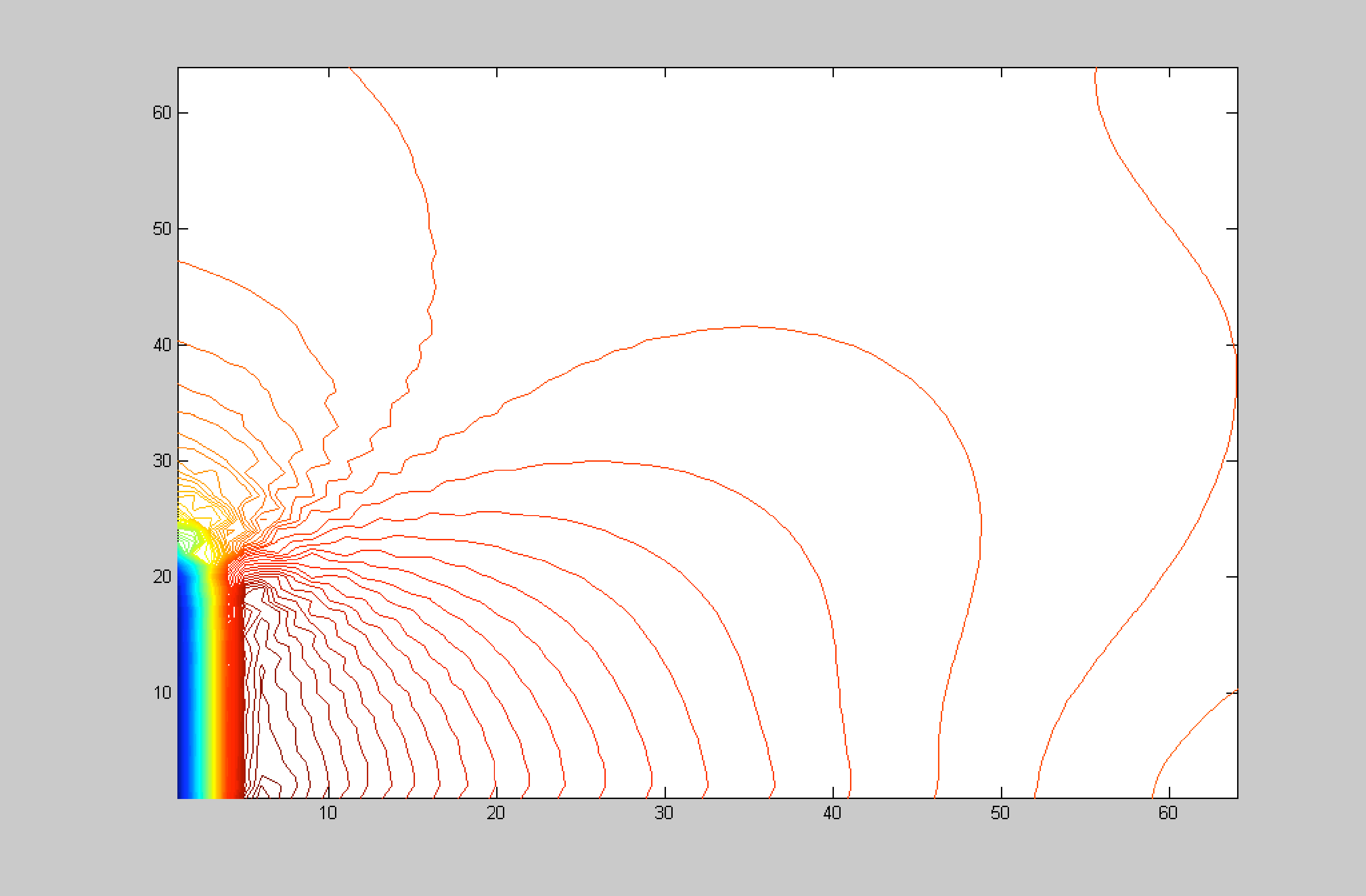
$$s = -\frac{u_r}{r}, a_z = \frac{v}{r}\frac{\partial u_z}{\partial r} + \frac{q}{m}\frac{\partial \phi}{\partial z}\frac{\partial f}{\partial v_z}, a_r = \frac{v}{r}\left(\frac{\partial u_r}{\partial r} - \frac{u_r}{r}\right) + \frac{q}{m}\frac{\partial \phi}{\partial r}\frac{\partial f}{\partial v_r}$$

Results

- Compare general trends: non-dimensional
- Compare specific cases

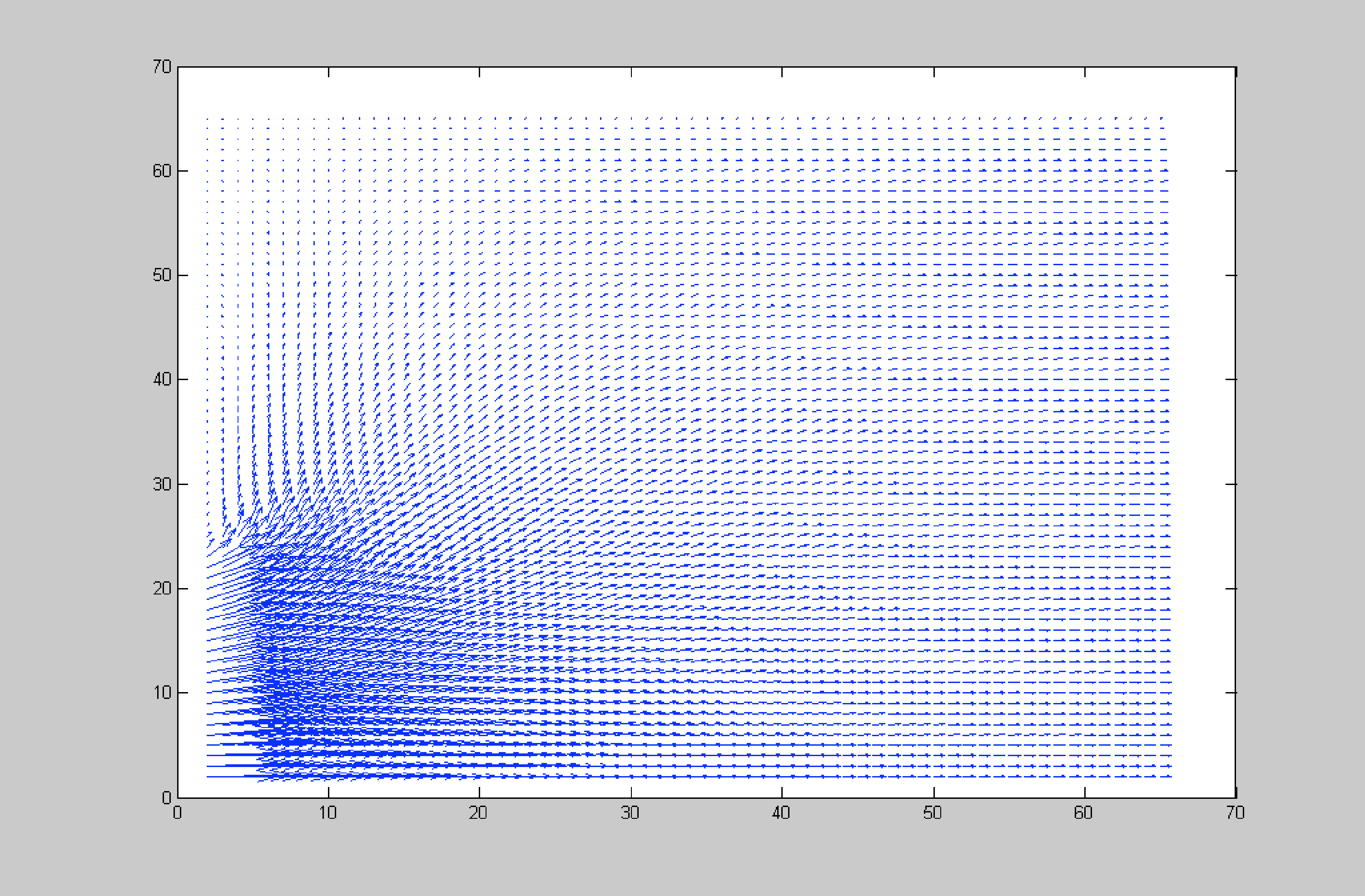
LBM Ion Thruster Exhaust Stream

Unitless ion #density contours; matches Crawford (2001)



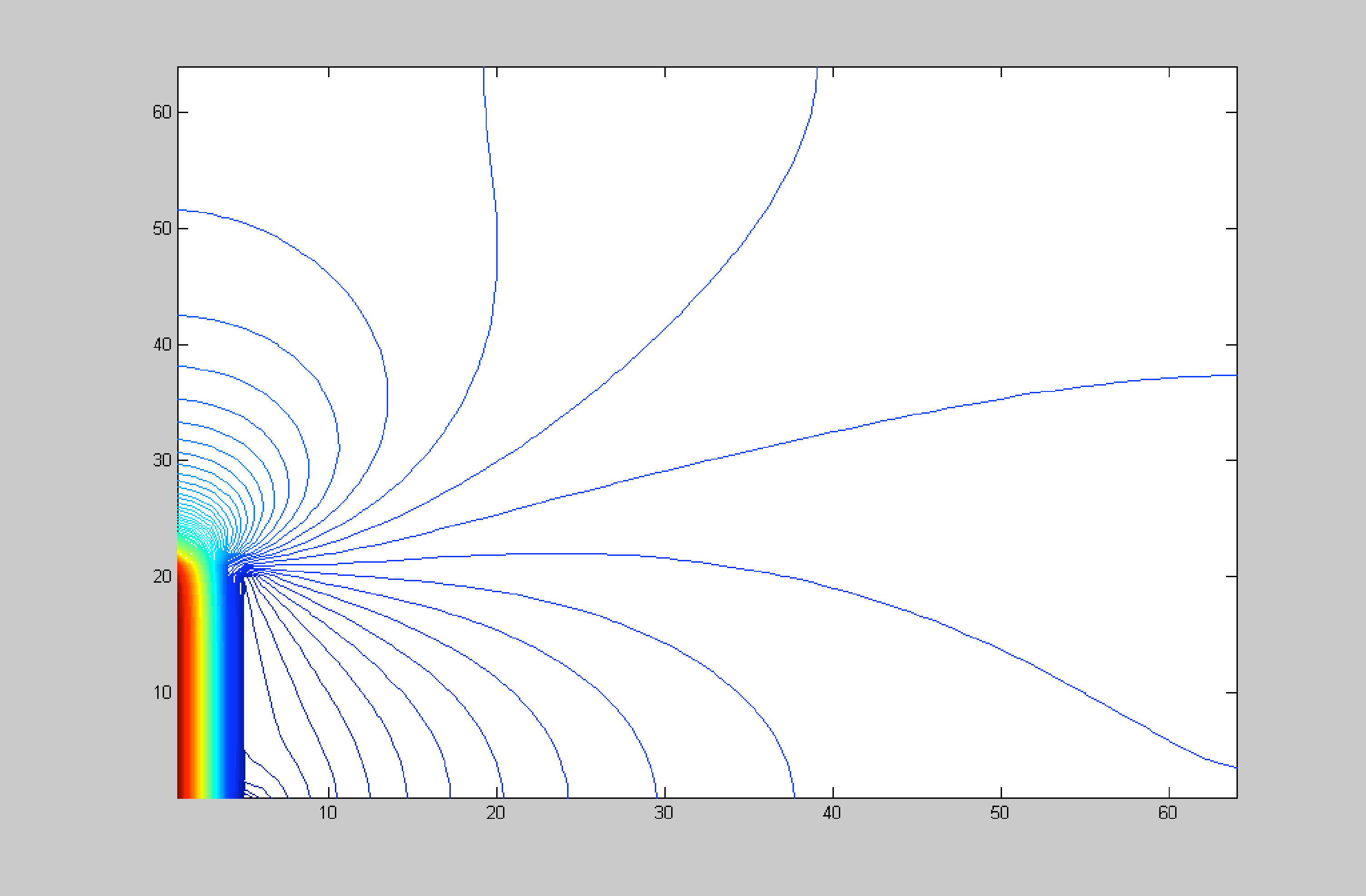
LBM Ion Thruster Exhaust Stream

Ion velocity field



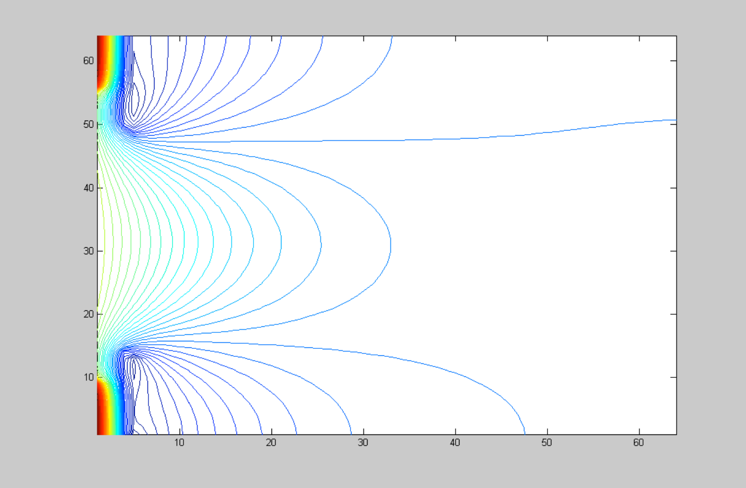
LBM Ion Thruster Exhaust Stream

Electrostatic potential

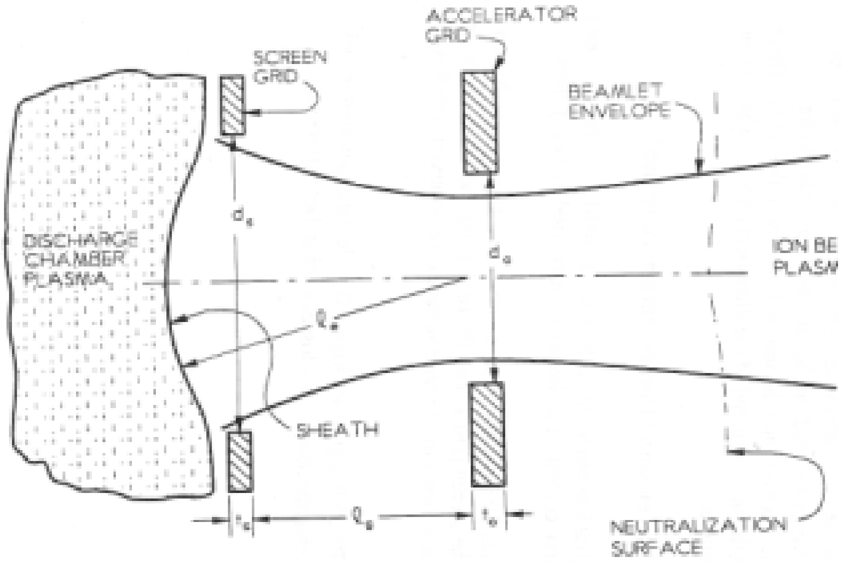


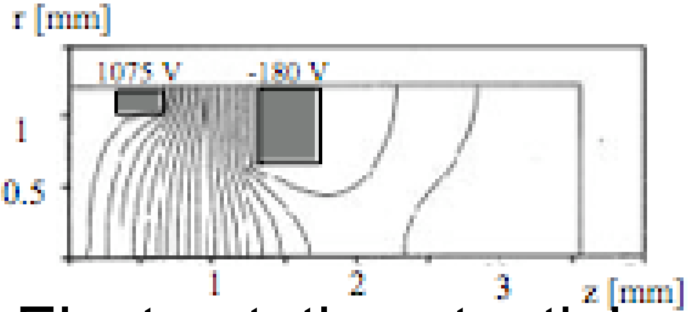
LBM Models of Ion Thruster Optics

- 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 btwn grids

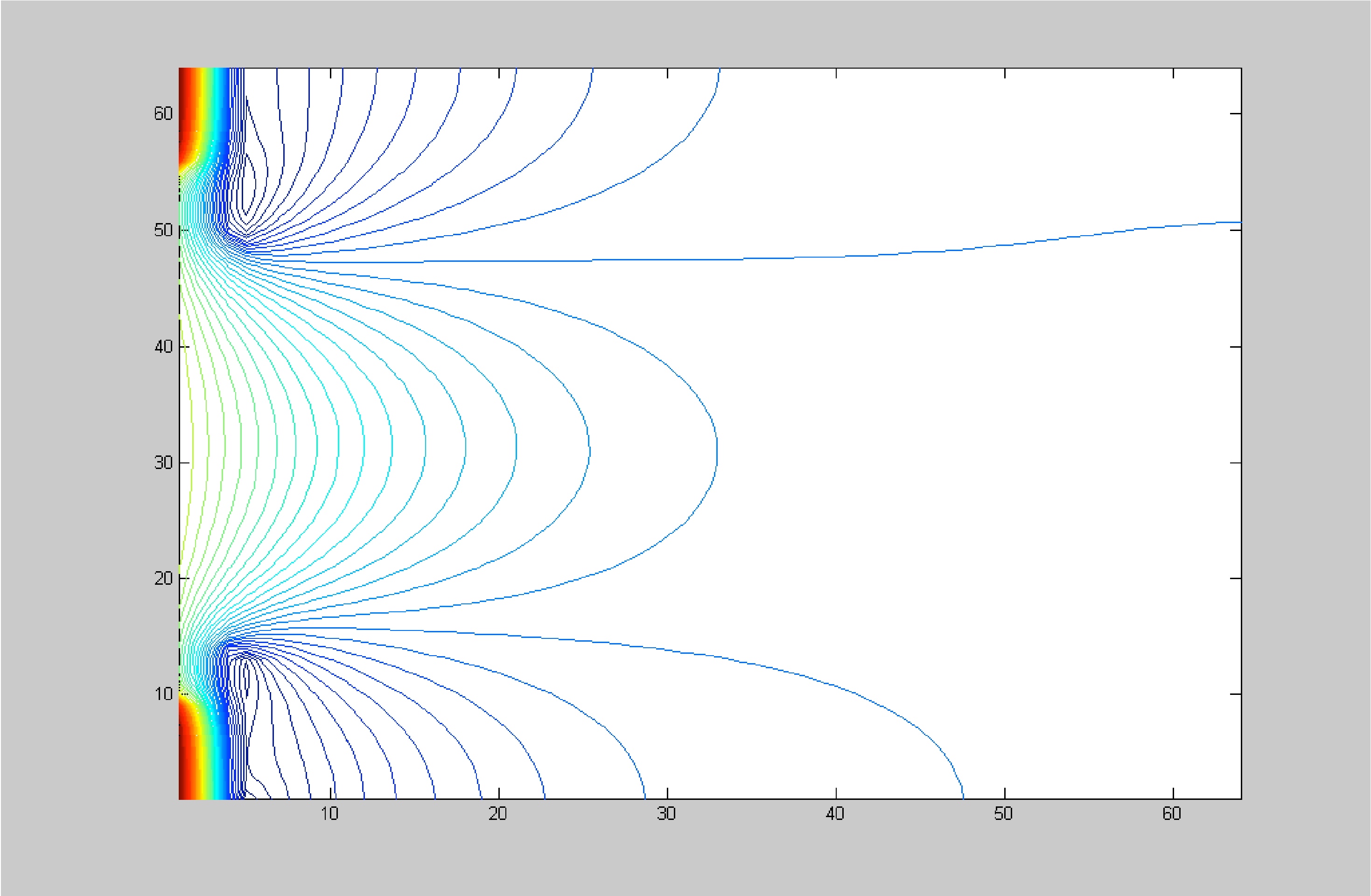




Electrostatic potential contours from Duchemin (2001)

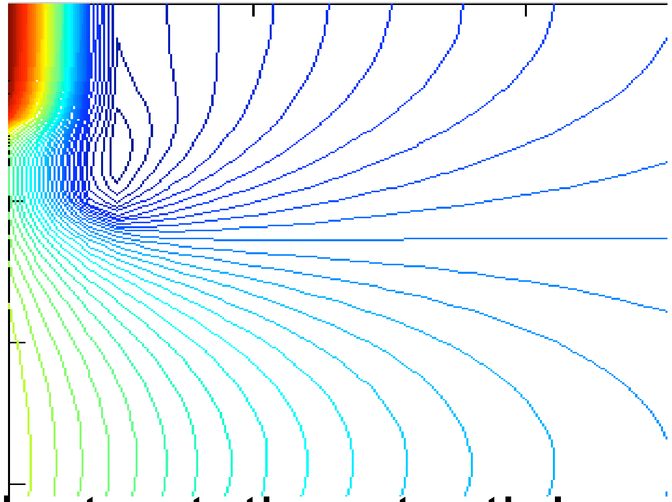
LBM Ion Thruster Optics

Electrostatic potential

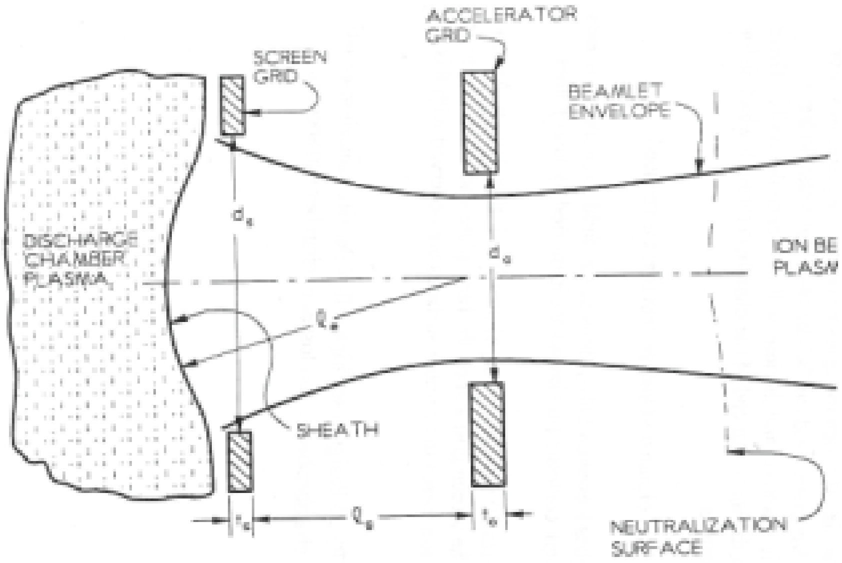


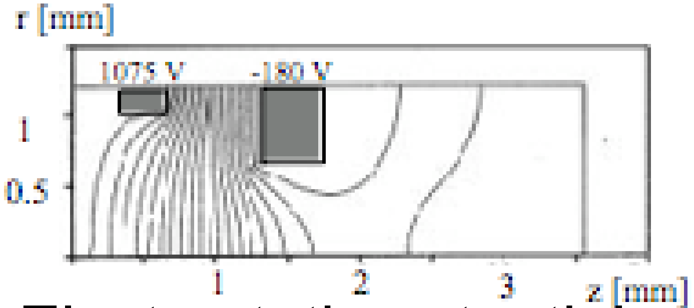
LBM Models of Ion Thruster Optics

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



Electrostatic potential contours from modeling a slit btwn grids

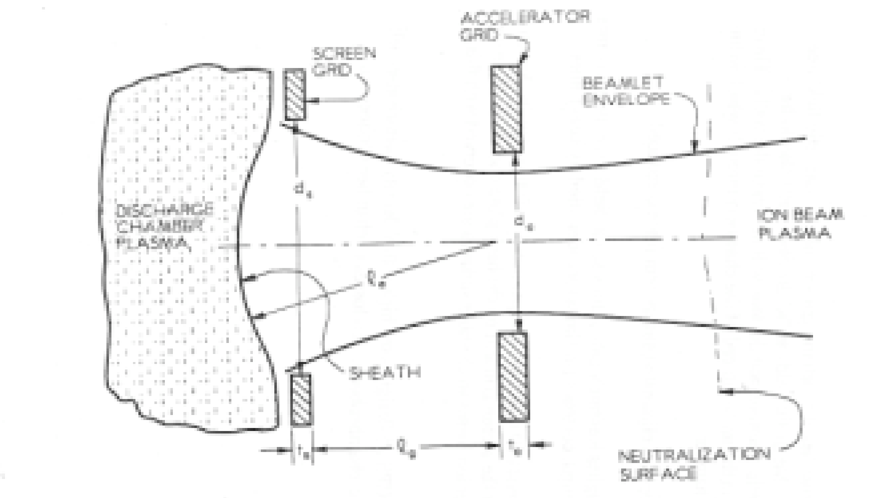


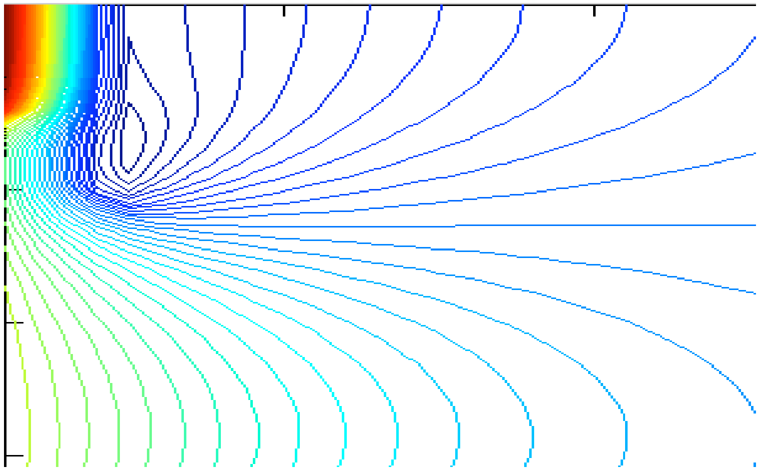


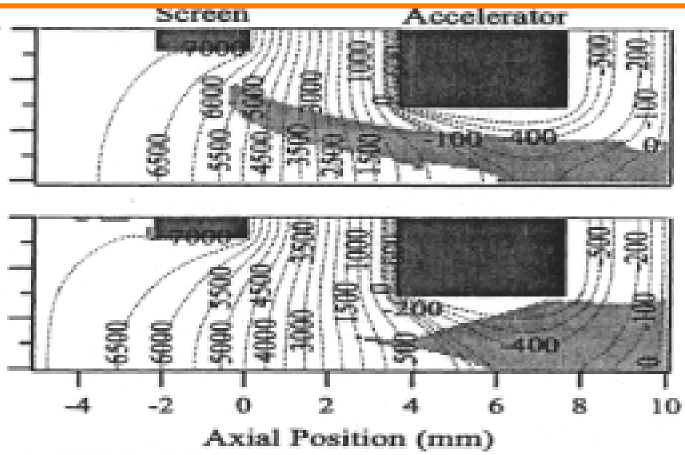
Electrostatic potential contours from Duchemin (2001)

LBM Models of Ion Thruster Optics

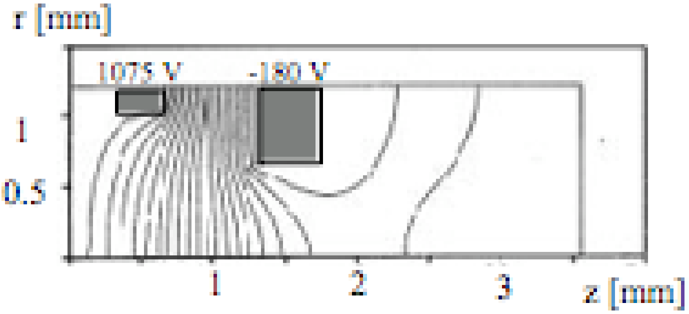
Electrostatic potential btwn grids





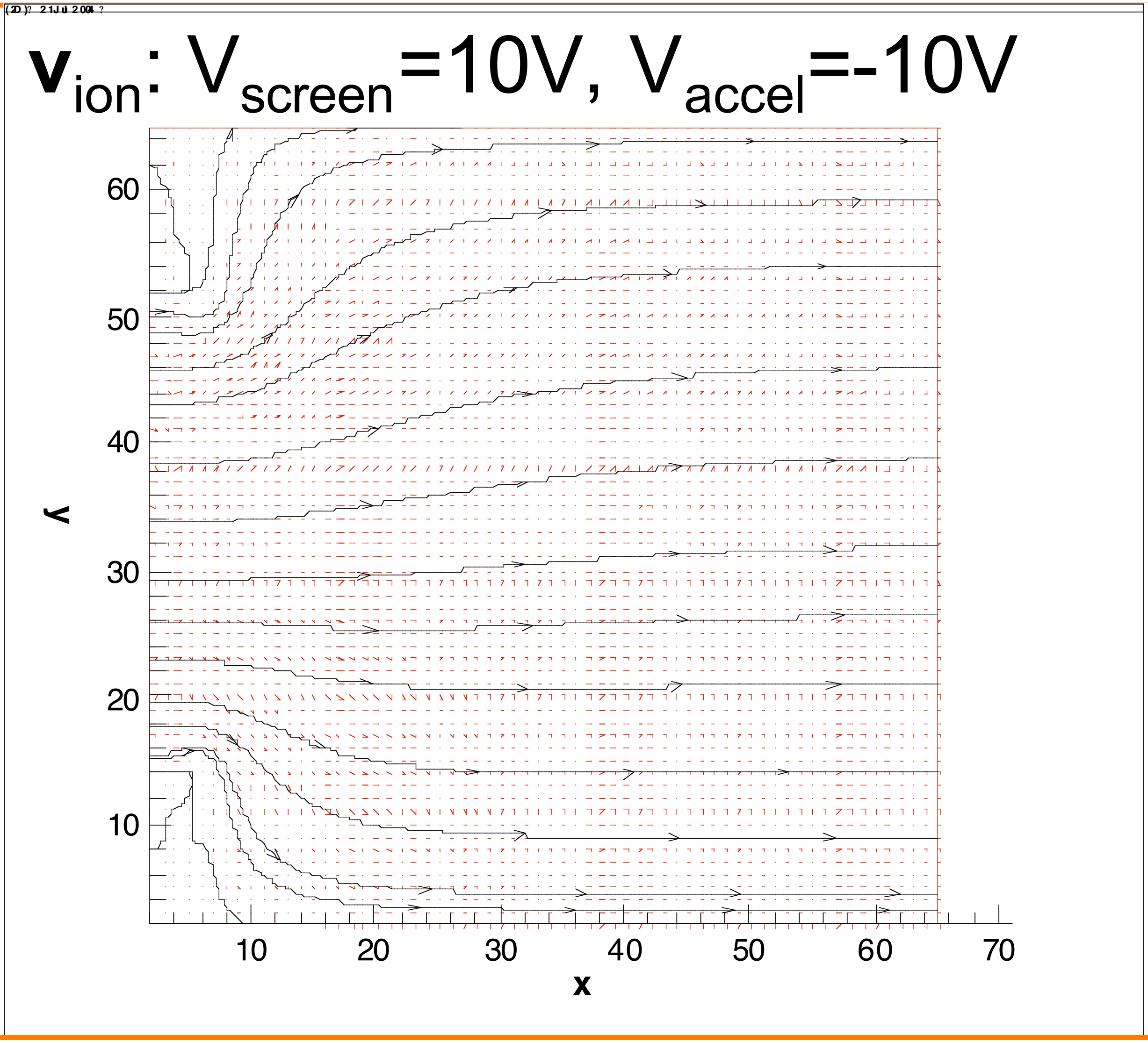


Electrostatic potential contours from Gallimore (2004)



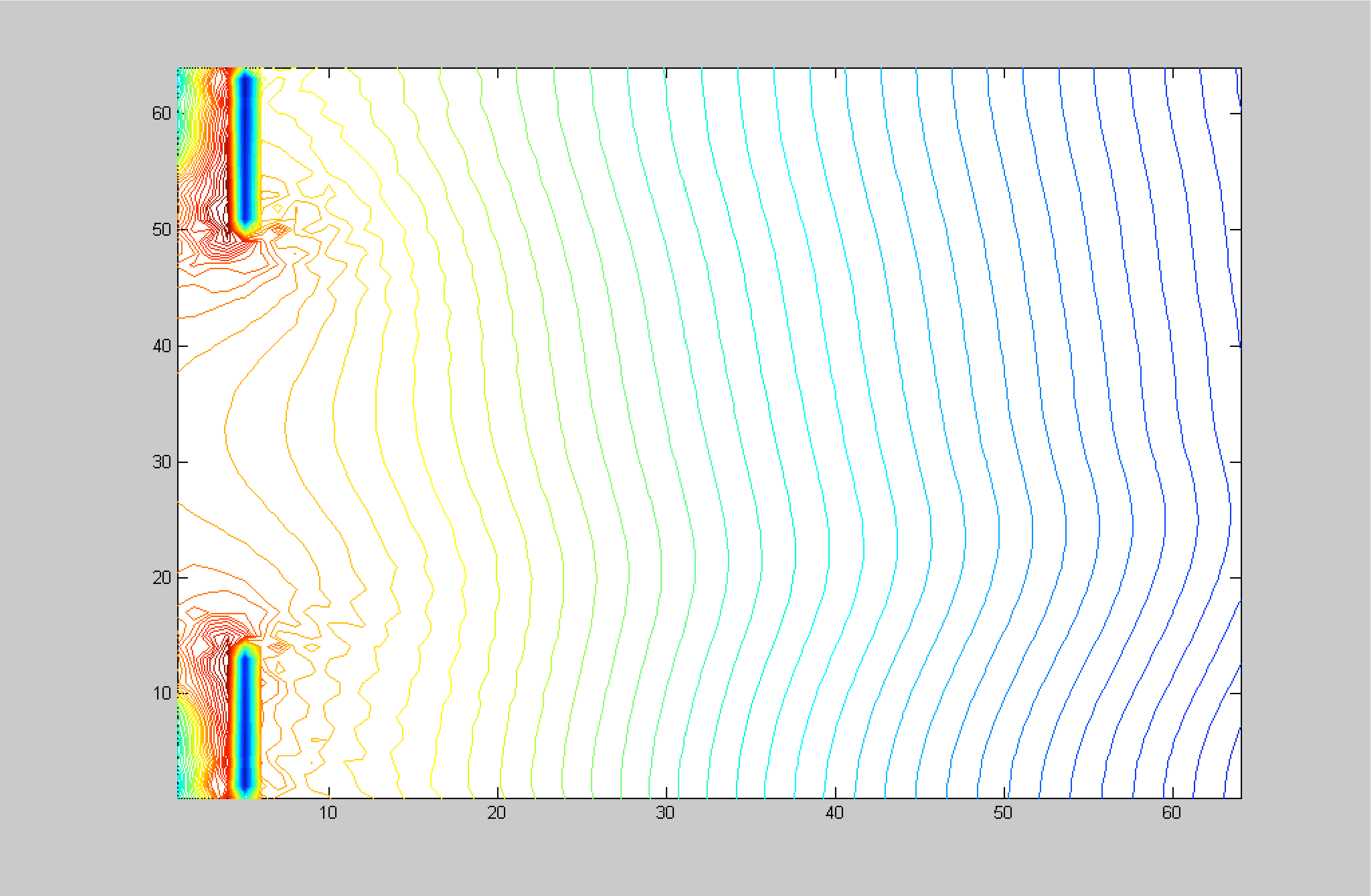
Electrostatic potential contours from Duchemin (2001)

LBM Ion Thruster Optics



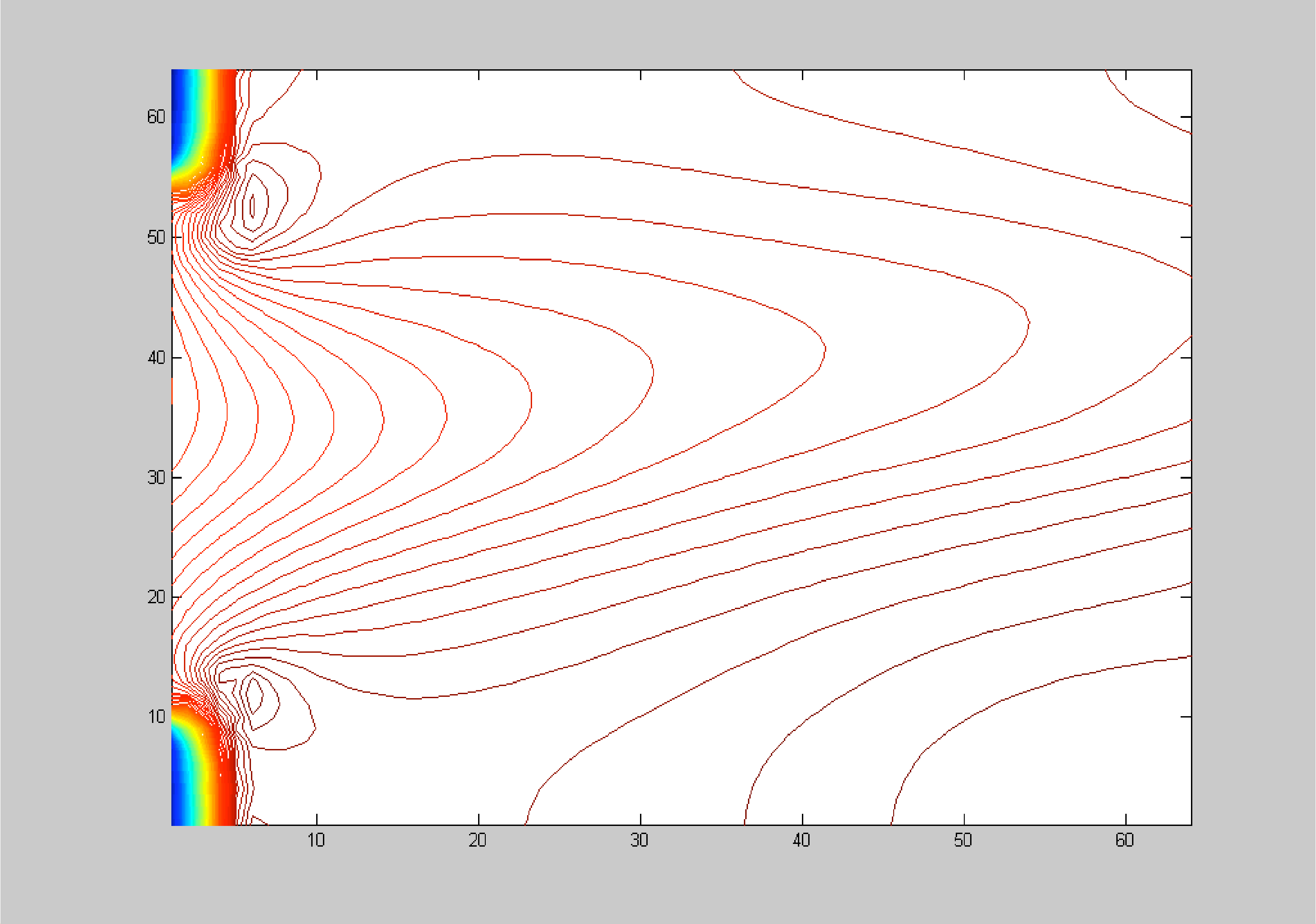
LBM Models of Ion Thruster Optics

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



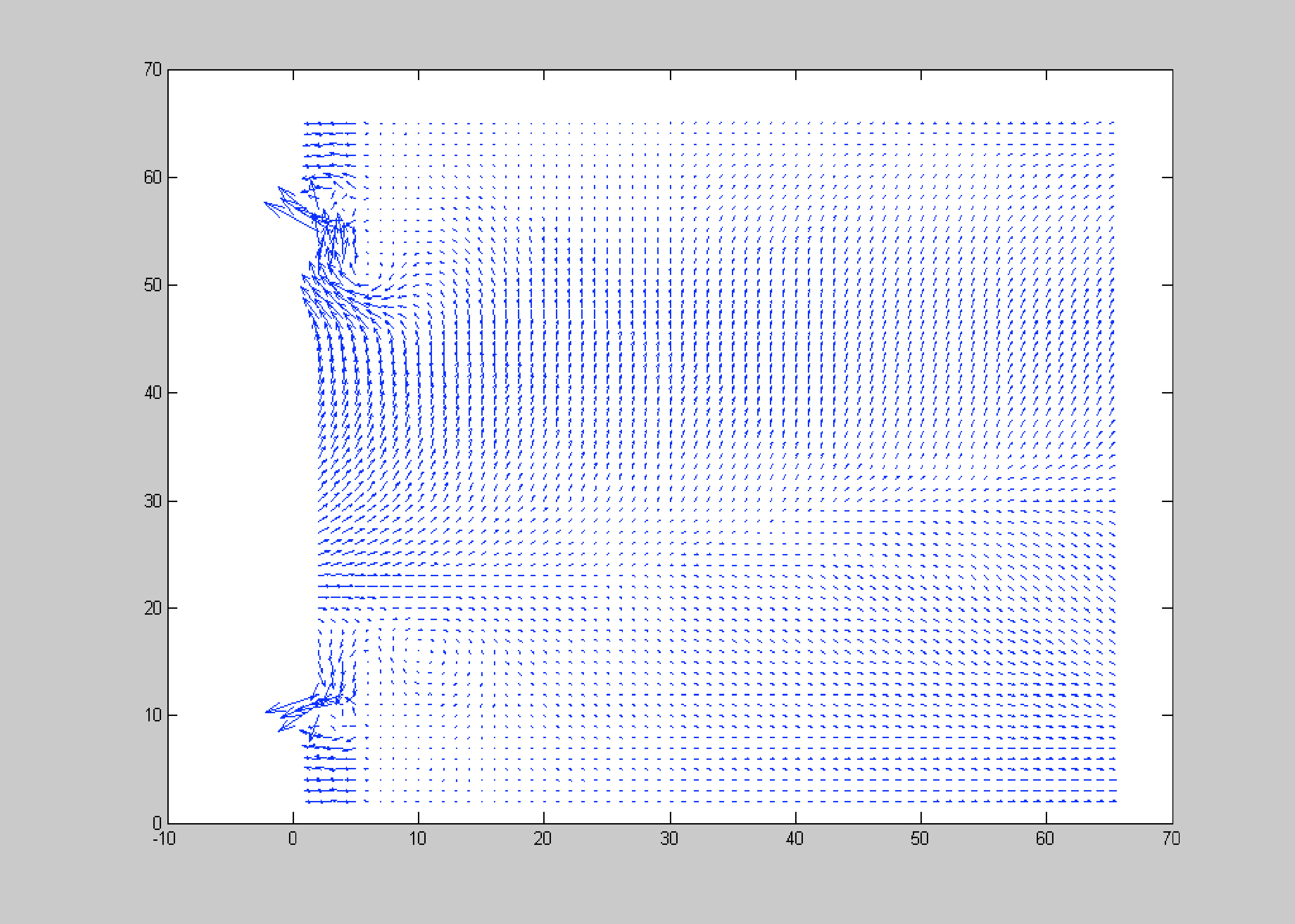
LBM Models of Ion Thruster Optics

Ion # density; screen grid 1075V, accelerator grid -180



LBM Models of Ion Thruster Optics

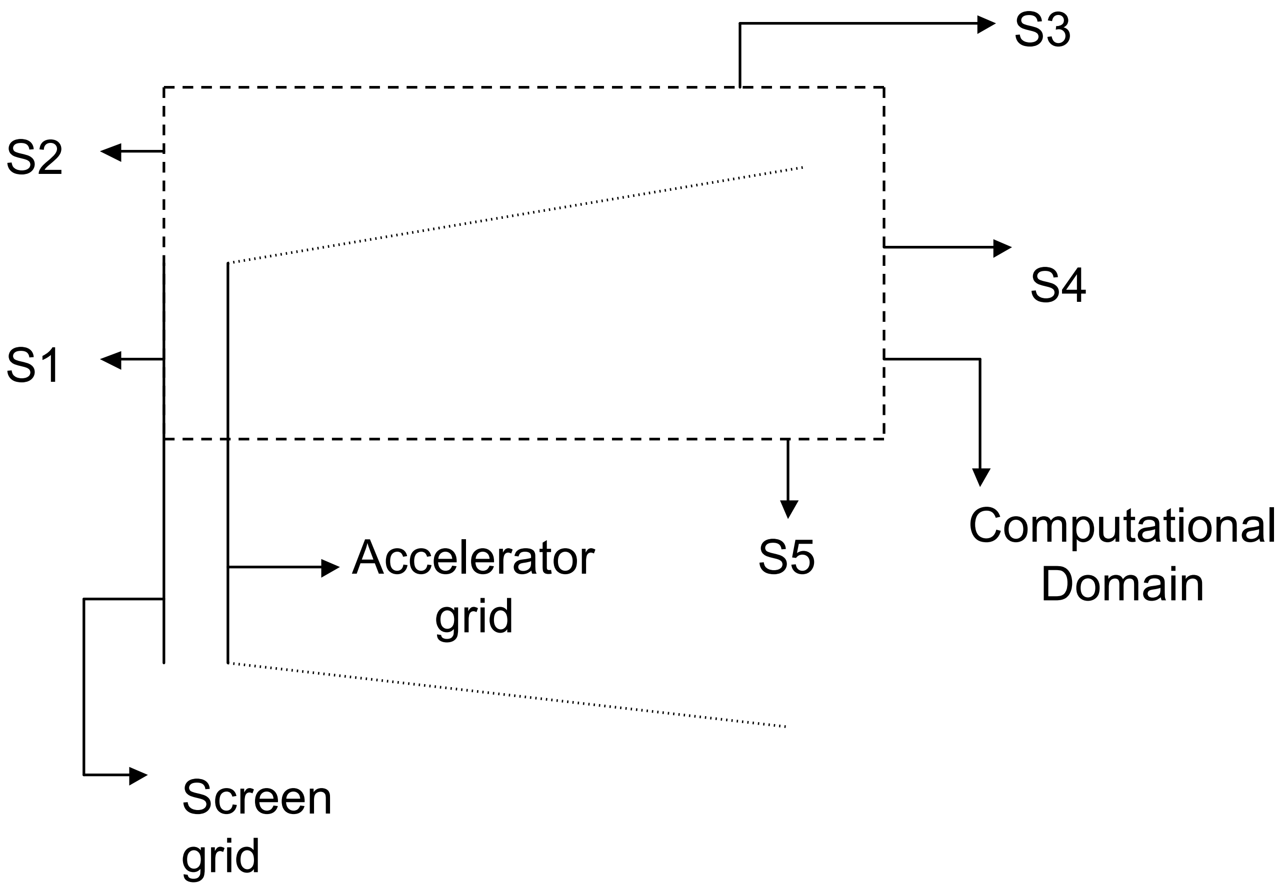
Ion velocity field; screen grid 1075V, accelerator grid -180



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

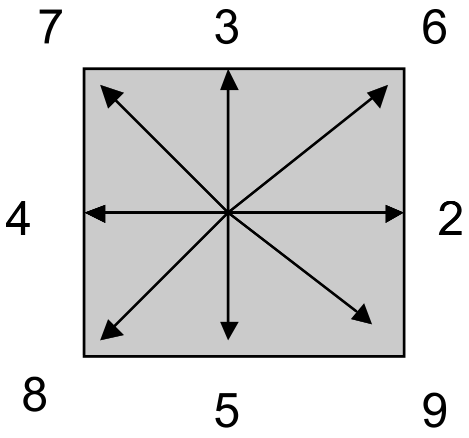
Computational Domain



Extrapolation Boundary

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

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



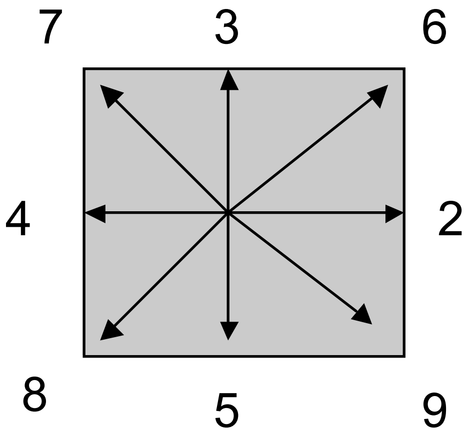
- At S4,
  - $f(NX,j,8) = f(NX-1,j,8)$
  - $f(NX,j,4) = f(NX-1,j,4)$
  - $f(NX,j,7) = f(NX-1,j,7)$

Free stream boundary

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

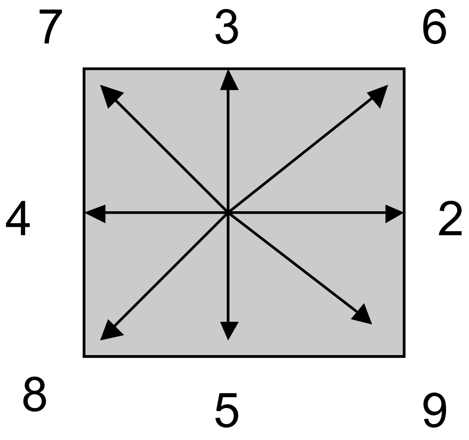
- At S2,
  - $f(1,j,9) = 0.0$
  - $f(1,j,2) = 0.0$
  - $f(1,j,6) = 0.0$

- 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,
  - $f(i,1,7) = f(i,2,8)$
  - $f(i,1,3) = f(i,2,5)$
  - $f(i,1,6) = f(i,2,9)$