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COMSOL Multiphysics® Software Used as a Laplacian Potential Simulator for an Electrospray Propulsion System Extraction Region

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Clarkson University Aeronautical Engineering '16

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COMSOL CONFERENCE 2015 BOSTON

Summary

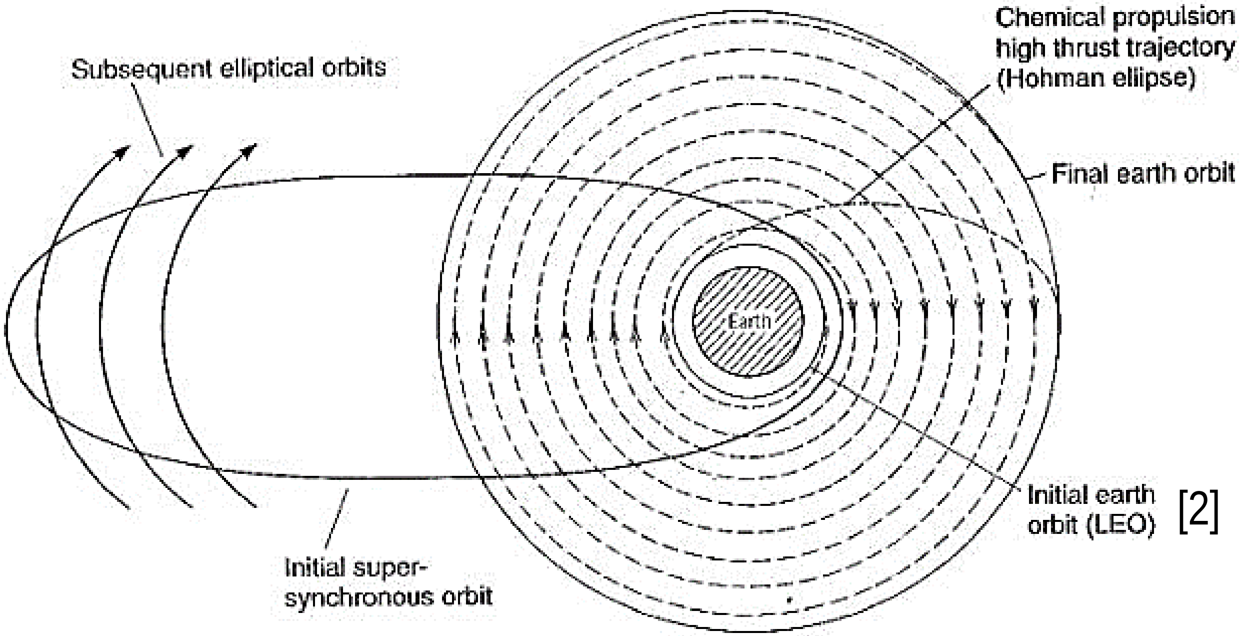
- Electric propulsion
  - Electrospray propulsion
- Mathematical Basis of Electrospray
  - Extraction Region
- Methodology
- Results
- Supporting/Future Work

Astrodynamics of Electric Propulsion

- Tsiolkovsky's Rocket Equation can be used as a basis on moving in space:

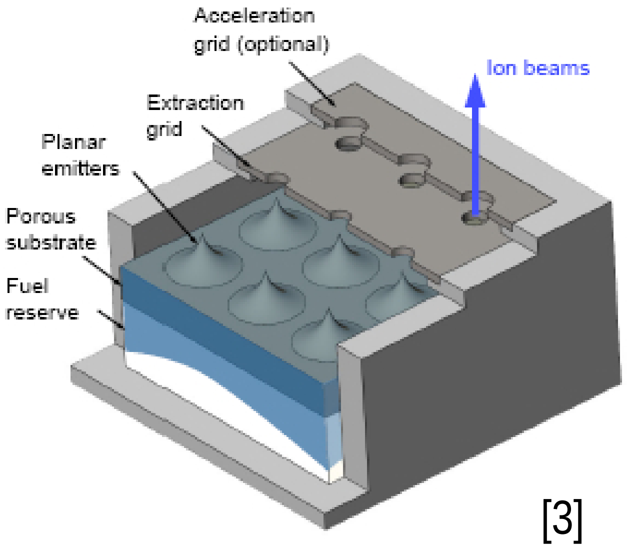
$$\Delta V = I_{sp} * g_0 * \ln\left(\frac{m_{full}}{m_{empty}}\right); I_{sp} = \frac{\Sigma Impulse}{\dot{m} * g_0}$$

- ~6km/s to Mars LEO, or a 4:1 full/empty ratio with a 450s Isp
  - Electrospray propulsion may achieve an I_{sp} of 2000-3000 seconds compared to 450 for chemical

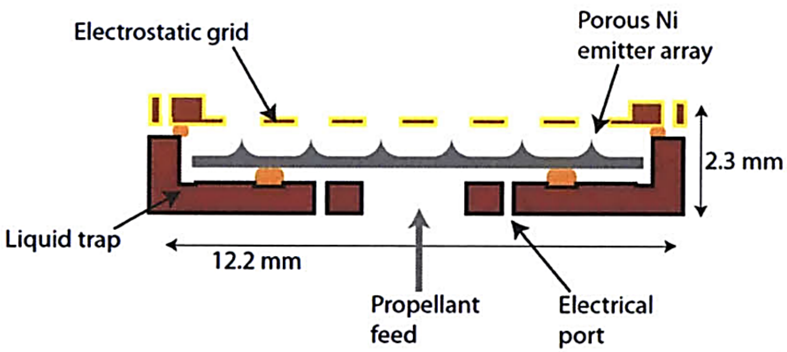


[2]

Electrospray Propulsion



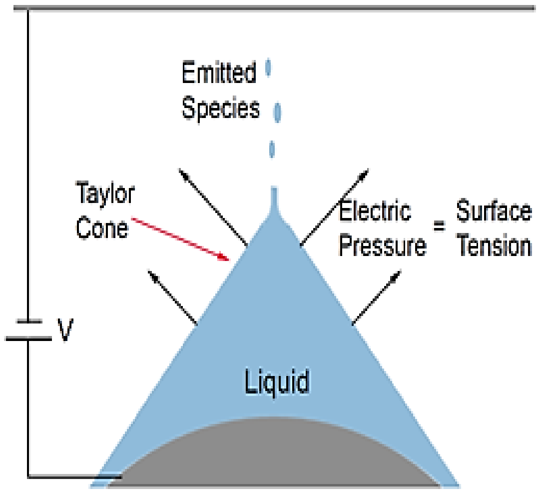
[3]



- Mechanically-simple system
  - MEMS fabrication allows for mass production
  - No pumps, which need ~10s watts
- Taylor cones formed by electric fields induced in the thruster -> molten salt emitted through grid
- Uses ionic liquids
  - Ionic liquids aim to avoid impingement concerns of metal propellants

Extraction Region

- Electrostatic field draws particles from "tank"
  - In iEPS, through a porous layer that blocks passive unpowered flow
  - Particles drawn towards unlike charge, are neutralized
- Taylor cone is formed between source and extractor grid
  - At the tip of the cone, the electrical relaxation and fluid residence times converge and particles are expelled into a plume
  - Ionic sources at >10μm distances found to minimize chance of interactions between cones

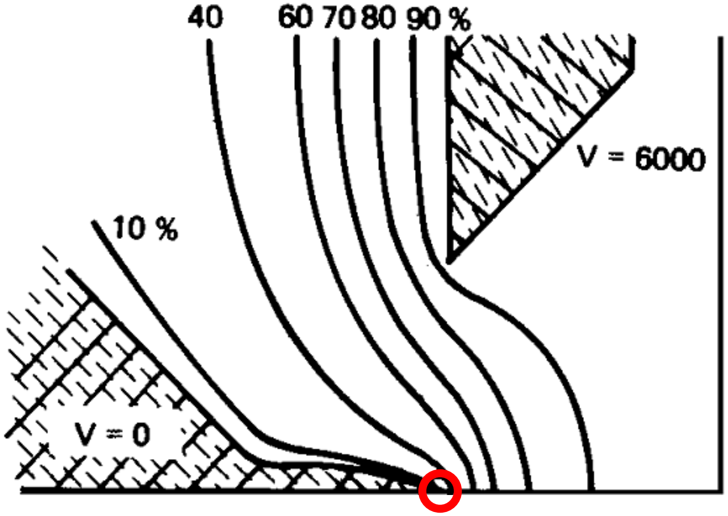


[3]

- Following extraction from grid, plume expands
  - Higher current = higher angles, coaxial trends
  - Downstream plume divergence dependent on extraction region + space charge

$$I = f(\varepsilon)\sqrt{\frac{\gamma K Q}{\varepsilon}}$$

Extraction Region



[5]

- Taylor cone boundary equipotentially 0V
  - Within and outside of the cone, charge decreases away from red circle
- Whole system considered to be stationary
- Widely variable scale (1000Å -> 150000Å)

- Conventional extraction region voltage model:

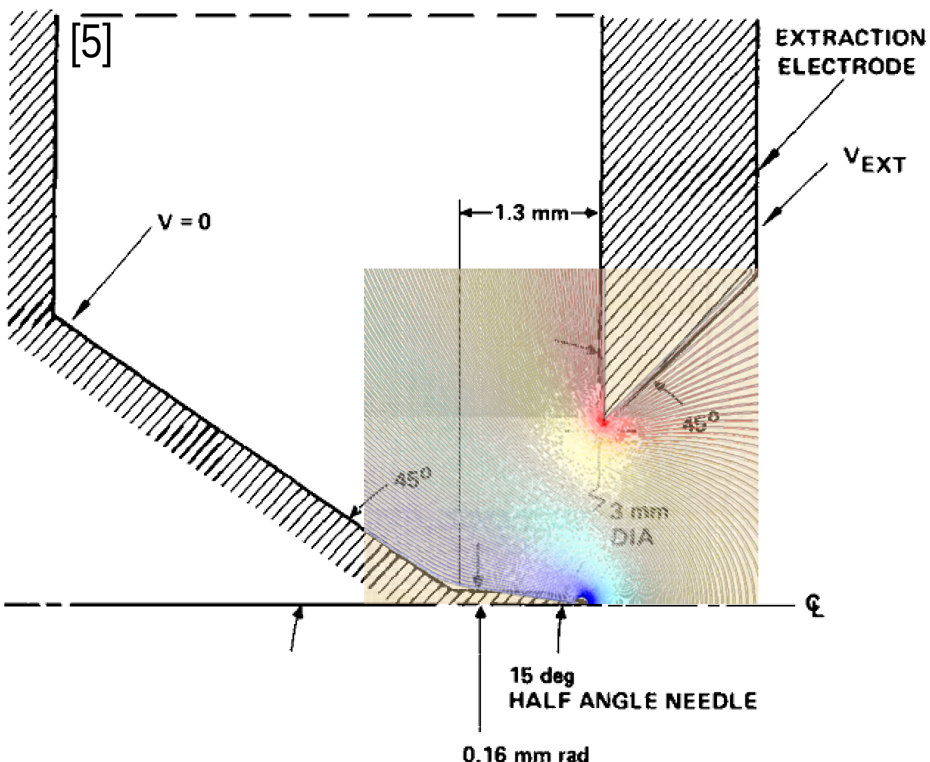
$$V(r,\theta) = V_r * \left(\frac{a}{R}\right)^n * \left(\left(\frac{r}{a}\right)^n - \left(\frac{a}{r}\right)^{n+1}\right) \times P_n * \cos(\theta) - V_0$$

- Consequently defines electric field strength:

$$E = -\nabla V$$

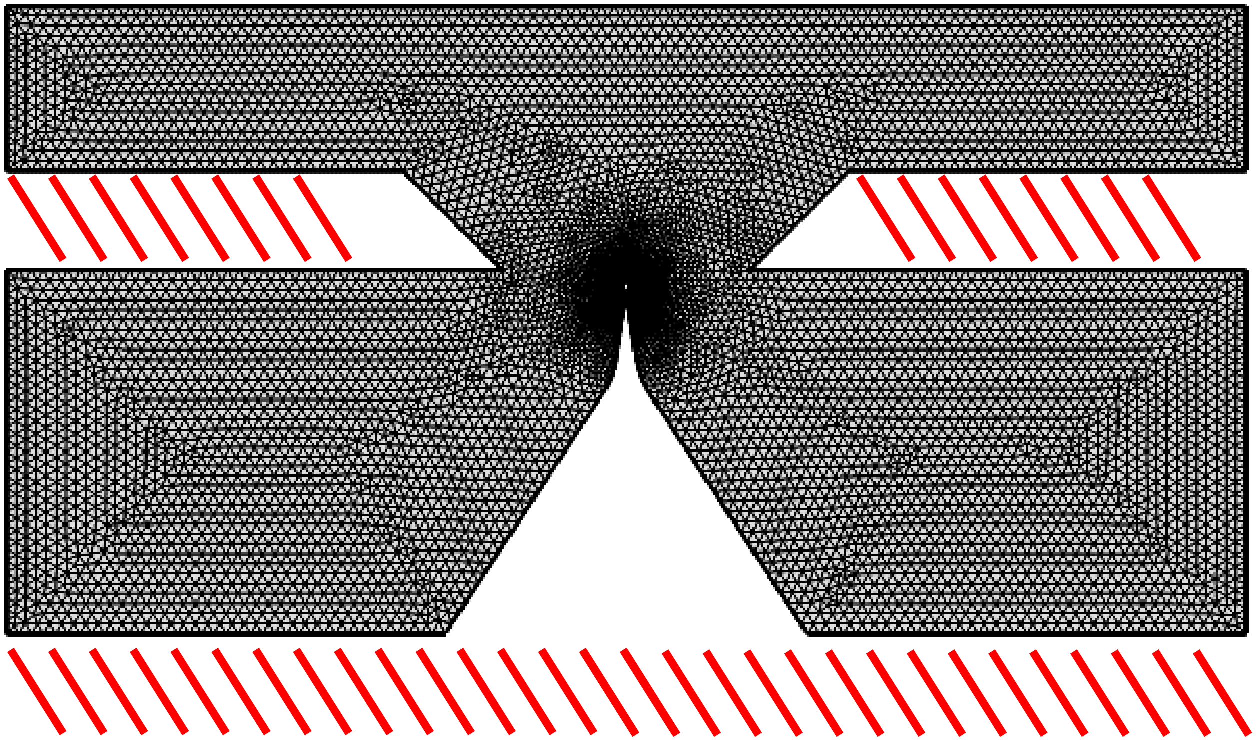
Methodology

- Constructing Ga+ system in COMSOL Multiphysics to validate it as a tool through Voltage measurements
- Repeating process with unknown extraction region to characterize thruster system



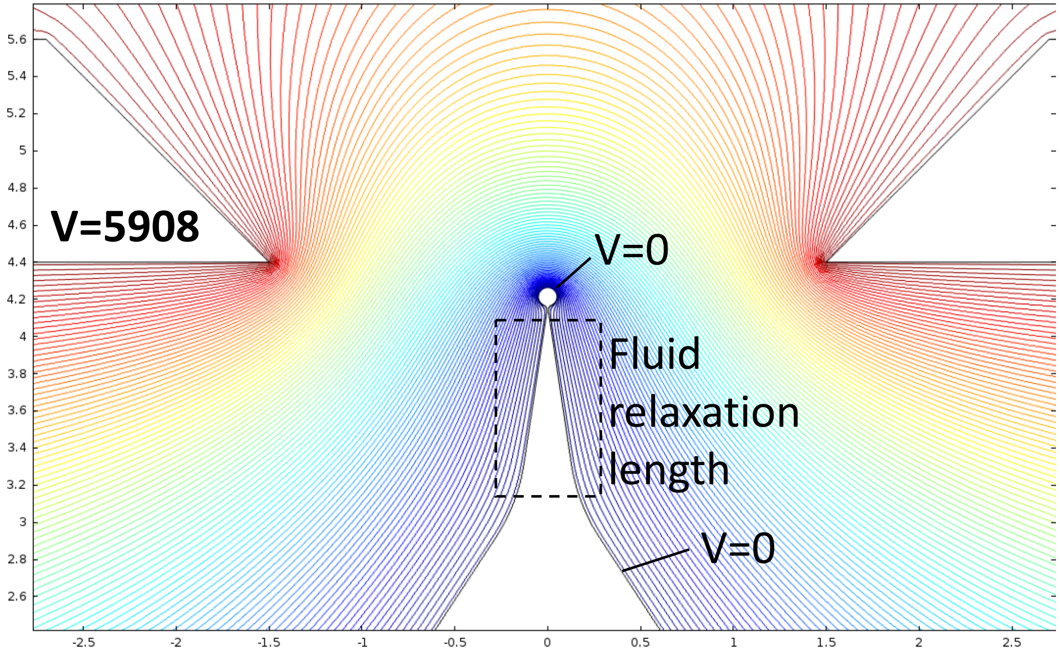
Methodology

- AC/DC stationary electrostatic field model
- Taylor Cone: 0V; Extraction grid: 5908V; free boundaries otherwise
- Simple model allowed for high grid density



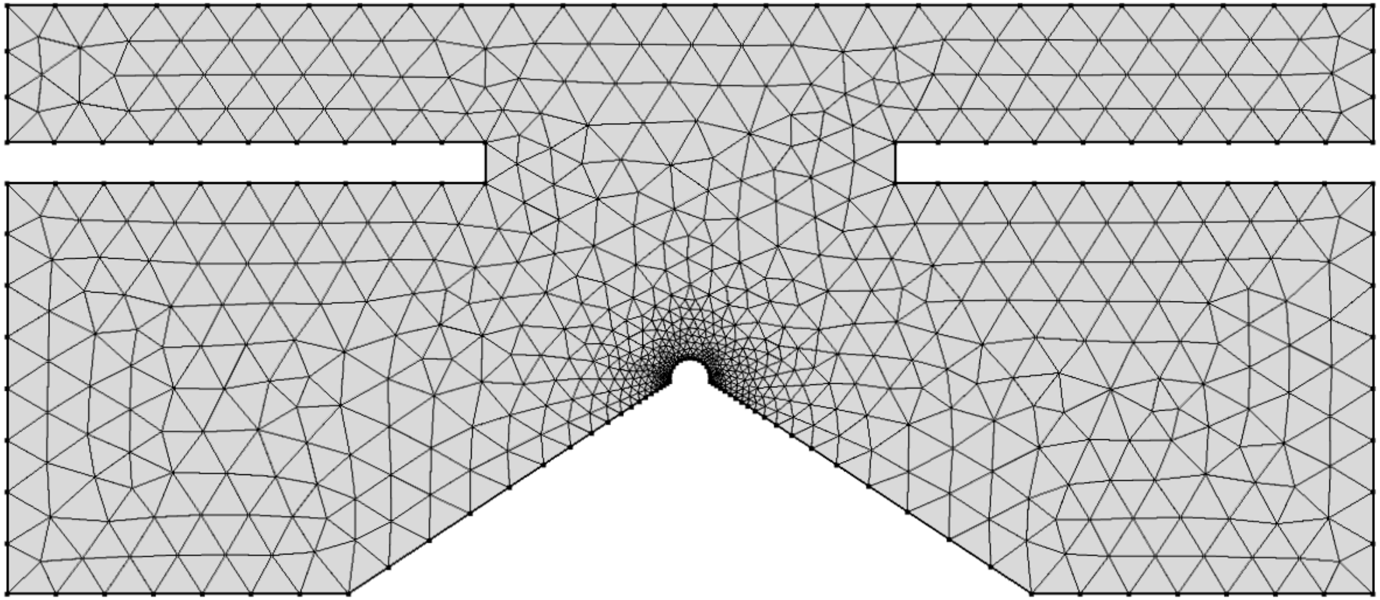
Methodology

- Geometry is used as stationary bounds in a steady state with e.g. a stationary spherical emission bead
- Voltage output to MATLAB and compared with SOC and Herrmannsfeldt



Methodology

- iEPS thruster model based around approximations
  - Scale study and interesting quantities were primarily sought
  - As seen in the figure, voltage potential trends could be predicted as per the Ga+ model



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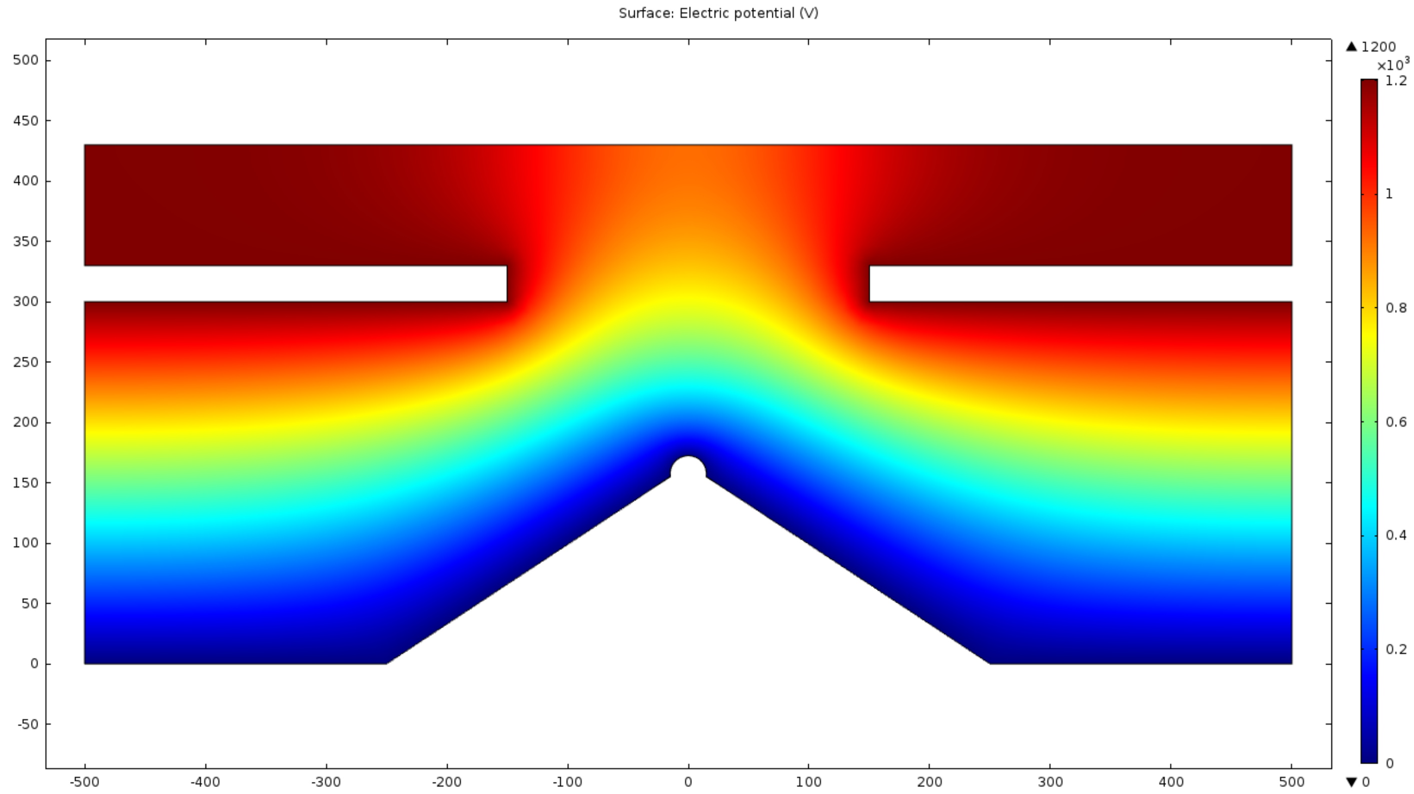
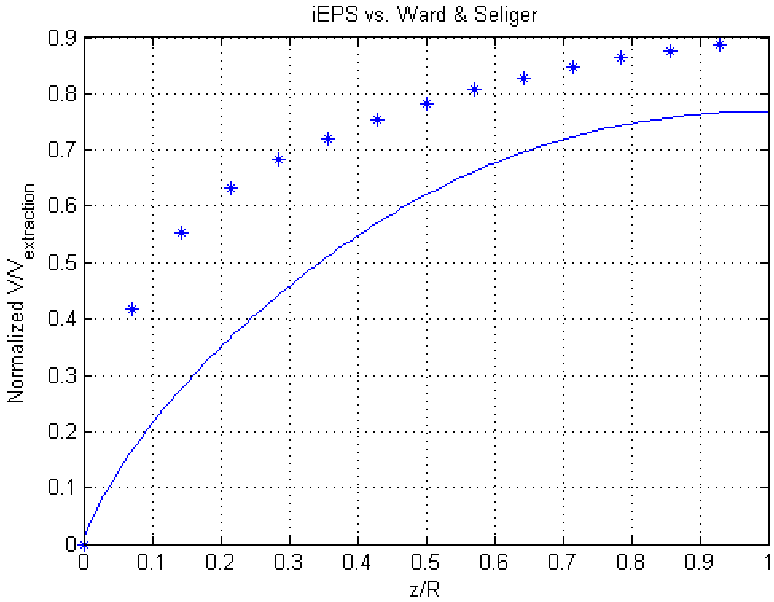
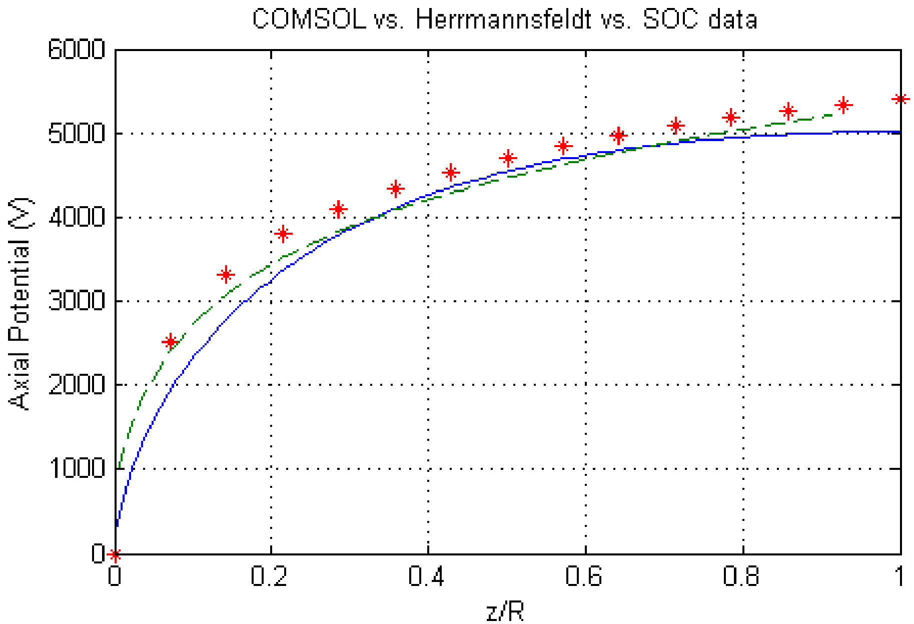


Results

- Rough large-area electric potential is found to follow parabolic trend despite voltage and scale change (1000 v. 150000Å emission bead)



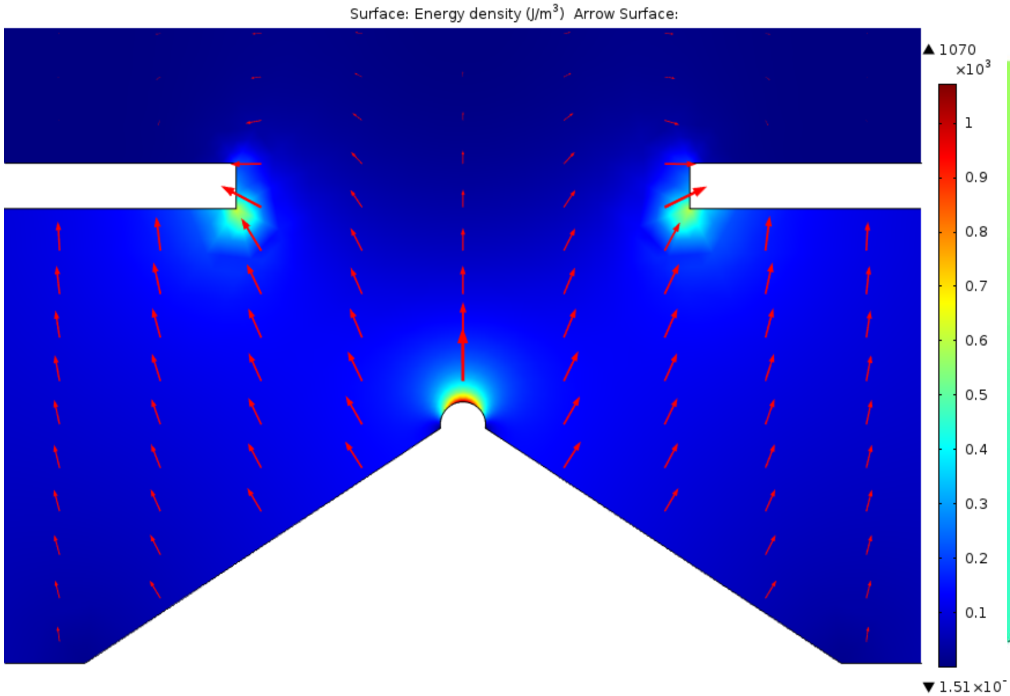
Comparison of iEPS (line) and Ga^+ extraction region (asterisk) normalized potential w.r.t. extraction grid voltage

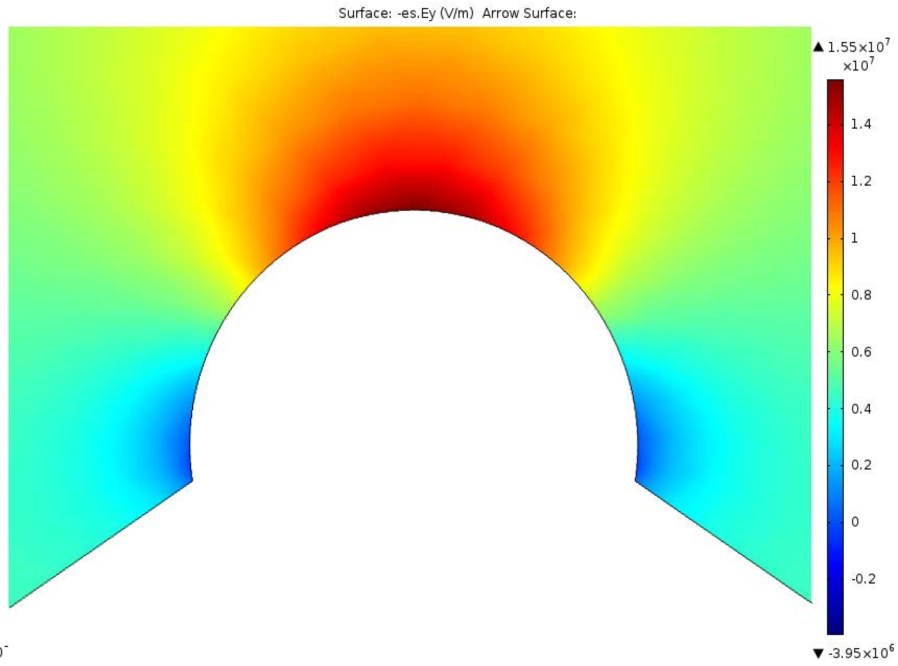


COMSOL (blue), Herrmannsfeldt (red), and SOC (green) data juxtaposed. z/R denotes a normalized scale from emission to extraction grid.

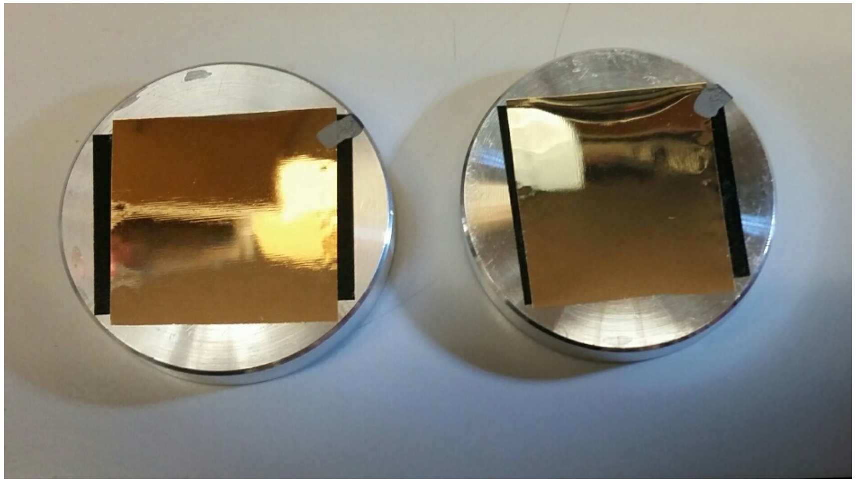
Results

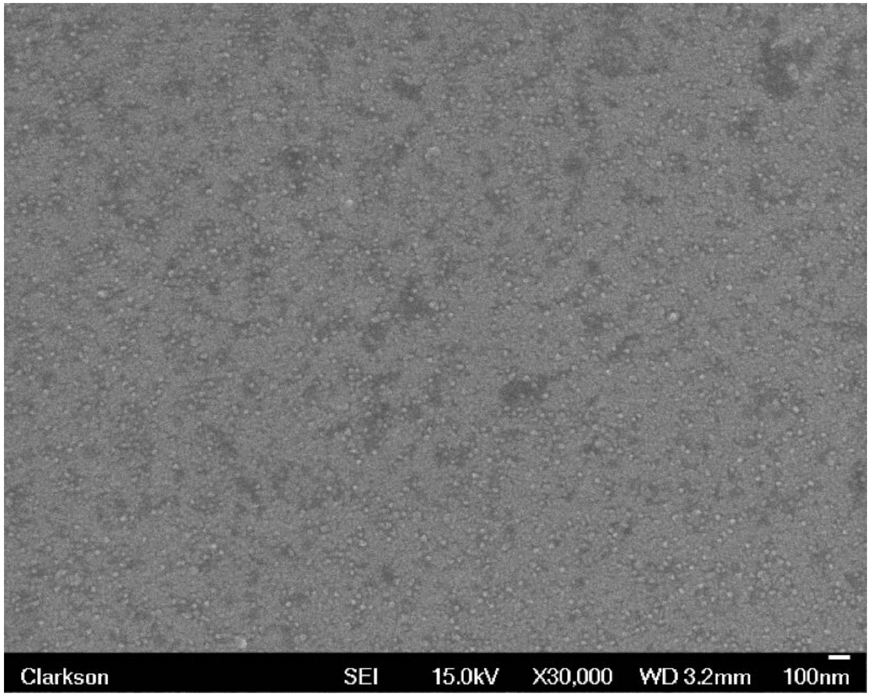
- Significant factors of particle movement drivers in the extraction region are shown by COMSOL Multiphysics:





Supporting Work





- Experimental deposition study
  - Field emission electron microscope conducting pre- and post-firing surface metrology study
- Data from post-study metrology of samples is useful as divergence data for comparison with existing experimental findings by MIT/Accion Systems

Future Work

- Time-dependent space charge build-up in extraction region plume
  - Space charge is dominant in far-downstream plumes
  - Determining Legendre functions for the EMI-BF_4 beam for proper SOC analysis of iEPS
- Optimize MATLAB particle trajectory algorithms and data utilization
  - Current trajectories inaccurate due to transition to MATLAB and ill-suited algorithms
- Juxtapose experimental study with previous divergence data, utilize them to support trajectory calculations

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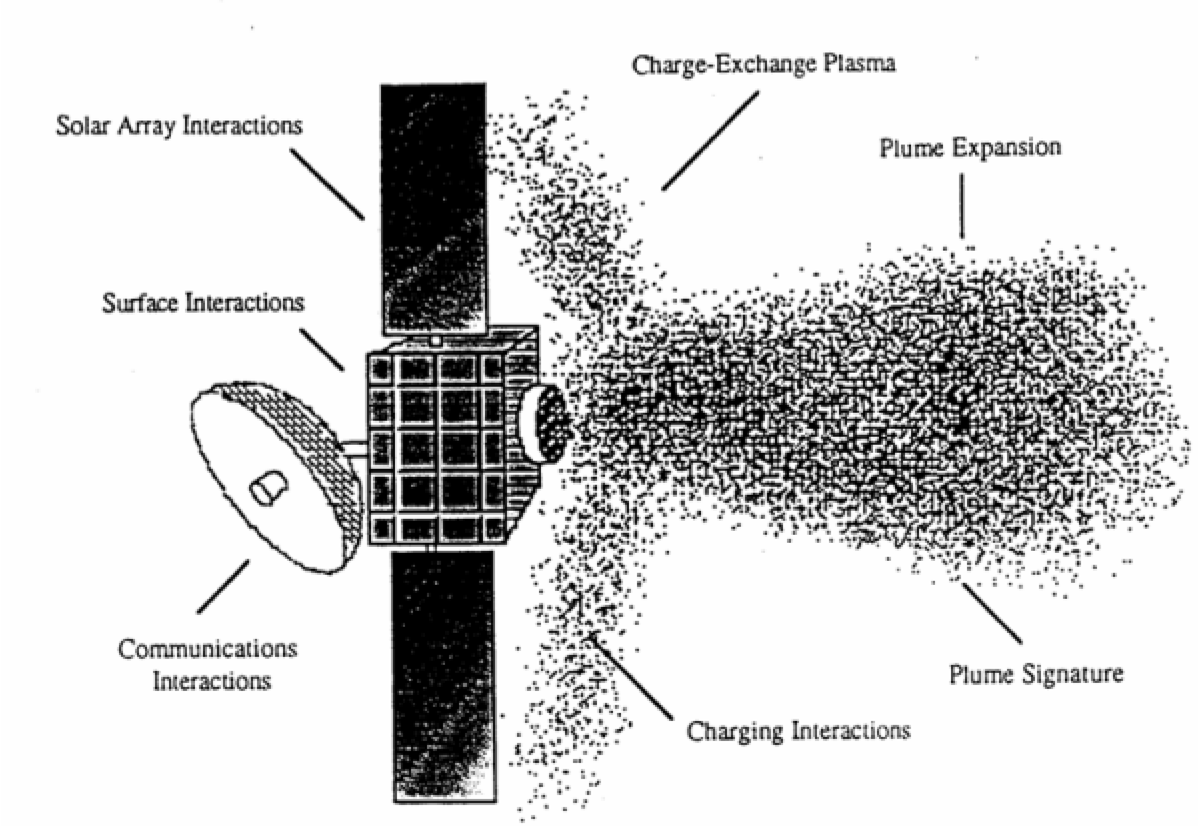
References

[1] Martinez-Sanchez, M., & Pollard, J. E. (1998). Spacecraft electric propulsion – an overview. *Journal of Propulsion and Power*, *14*(5), 688-699.
[2] Stanbury, Sarah. *Low Thrust Transfer to GEO: Comparison of Electric and Chemical Propulsion.* Retrieved from Colorado Center for Astrodynamics Research.
[3] Courtney, D. G. (2011). *Ionic liquid ion source emitter arrays fabricated on bulk porous substrates for spacecraft propulsion* (Doctoral dissertation, Massachusetts Institute of Technology).
[4] Gamero-Castaño, M. (2008). The structure of electrospray beams in vacuum. *Journal of Fluid Mechanics*, *604*, 339-368.
[5] Ward, J. W., & Seliger, R. L. (1981). Trajectory calculations of the extraction region of a liquid-metal ion source. *Journal of Vacuum Science & Technology*, *19*(4), 1082-1086.

Questions?



Charge-Exchange Plasma
Solar Array Interactions
Plume Expansion
Surface Interactions
Communications Interactions
Plume Signature
Charging Interactions