NEXT Multi Ion Engine Test:
Plume Modeling and Test Plans

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Abstract: Ground testing of multiple NEXT ion thrusters is scheduled to occur at NASA Glenn Research Center during late CY 2005. The test will feature three active NEXT thrusters plus a dummy, and will take place in a vacuum tank of length 21 meters and diameter 7.3 meters. This paper describes pre-test modeling performed using the *Nascap-2k* computer code.

I.   Introduction

G ROUND testing of multiple NEXT thrusters is scheduled to take place in tank VF-6 at NASA Glenn Research Center during the fall of 2005. The test configuration includes three active NEXT thrusters plus a dummy thruster in the fourth position, as well as a full complement of diagnostic probes. The objective of the test is to identify and quantify the beneficial and deleterious interactions between the engines, their plumes, and their controlling electronics. Specifically, the tests address the following four questions:

1) What is the effect of multi-thruster operation on ion thruster grid lifetime?
2) How are spacecraft structures affected by the plasma particle and fields distribution due to multi-thruster operation including gimballing?
3) How are performance parameters such as neutralizer margin and plume divergence affected by multi-thruster operation?
4) How is the dormant thruster affected by the ambient plasma environment produced by the multi-thruster array?

Pre-test modeling of the interacting plumes is being performed by Science Applications International Corporation (SAIC) using the *Nascap-2k* computer code.[1] *Nascap-2k* is a three-dimensional plasma modeling code that allows us to faithfully represent the test geometry, import the single engine plume, and generate and track the charge exchange ions to achieve self-consistent ion densities and electrostatic potentials. Distribution of charge exchange ion current to the engines, diagnostics, and ancillary surfaces can be calculated. By comparing the code predictions with the test results we can assess which of the code models are most in need of improvement. Ultimately, the model will be able to predict interactions of multiple ion engines under space configurations and conditions.

II.   Test Configuration

Multi-thruster testing will take place in vacuum tank VF-6 at NASA Glenn Research Center. The tank measures 7.6 m by 21m and has a pumping speed of approximately 300 kl/s on xenon. The test will involve three actual NEXT thrusters plus a dummy, arranged in a square array 64 cm on a side. Each active thruster will have its own neutralizer. The engines can be gimbaled and alternative neutralizer configurations may be tried.

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The multi-thruster array contains two separate suites of diagnostics. One diagnostics set is co-located with the thruster array itself, and contains an assortment of downstream facing retarding potential analyzers and Langmuir probes as well as a near field Faraday probe arm. Co-located with each neutralizer is a 6 mm diameter planar Langmuir probe used to make measurements of changes in the neutralizer plasma due to configuration changes. The dormant thruster optics plane is terminated with a dished simulator panel that is electrically isolated from the thruster anode. This biasable plate also contains a Langmuir probe and an RPA to assess the nature of plasma efflux flowing toward the array.

The second probe suite consists of a multi-Faraday probe rake used to assess the plume profile a few thruster diameters downstream of the array. The probe rake is translatable in two orthogonal directions using an x-y motion control system.   Co-located on the Faraday probe rake are emissive probes which will be used to assess the plasma potential in planes through the center line of the upper and lower thruster pairs of the 3 + 1 array and through the physical centerline of the full array.

III.   Modeling Input

A. Code Description

Nascap-2k is an interactive toolkit for studying plasma interactions with realistic spacecraft in three dimensions, developed by SAIC with funding from the Air Force Research Laboratory and NASA's Space Environments and Effects (SEE) Program. It is distributed by the NASA SEE Program. It incorporates the physics need to address problems appropriate to both tenuous (*e.g.*, GEO orbit or interplanetary missions) and dense (*e.g.*, LEO orbit) plasma environments.

Nascap-2k was chosen for this project because of
1. Its ability (through the use of the auxiliary program *ObjectToolkit*) to realistically represent the geometrical surfaces of the test configuration;
2. Its ability to grid the volume within the chamber with variable resolution in order to accurately represent both the near and far plume fields;
3. Its ability to import plume structures and locate and orient them appropriately;
4. Its ability to calculate potential structures in plasma taking account of biased object surfaces;
5. Its ability to generate and track charge exchange ions to obtain space charge density, and iterate to a self-consistent potential solution.

The code procedure for this simulation is as follows:
1. Initialize the ion density with the superposition of the total ion density (main beam plus charge exchange) of each of the three thruster plumes, together with the ambient density;
2. Calculate the potential using the given ion density and electron density $n_e = n_0 \times \exp(e\varphi/kT_e)$, where n_0 is the "ambient plasma density" and T_e is the electron temperature;
3. Generate charge exchange ion macroparticles from the total neutral density (ambient neutrals plus neutral efflux from thrusters and neutralizers) and the main beam ion flux from each of the active thrusters;
4. Track the charge exchange ion macroparticles to obtain new charge exchange ion densities;
5. Return to (2), with the new ion density being the sum of the calculation charge exchange density and the main beam ion densities from the thrusters.
6. Iterate to self-consistency.

Output from the code includes space potentials and electric fields, charge exchange ion density, sample ion trajectories, and charge exchange ion currents to surfaces.

B. Single Thruster Plume Model

The model for the NEXT thruster plume was developed for an earlier study of observed erosion of the NEXT and NSTAR neutralizer tips.[2] To develop initial conditions for the plume model, we first used JPL's CEX2D[3] code to characterize the beamlet angular distribution as a function of beamlet current. Based on experimental measurements of the current density as a function of distance from the thruster centerline, we calculated the far-field angular distribution of the main beam ions. A specification of ion angle as a function of radius was then developed to give the same far-field angular distribution. Figure 1 shows the current density and angle versus radius used as

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initial conditions. The *PlumeTool* code (part of *EPIC – Electric Propulsion Interactions Code*[4]) was then used to propagate the main beam ions into space, creating a file of density and velocity as a function of angle and distance. The *PlumeTool* density field for the main beam ions is shown in Figure 2.
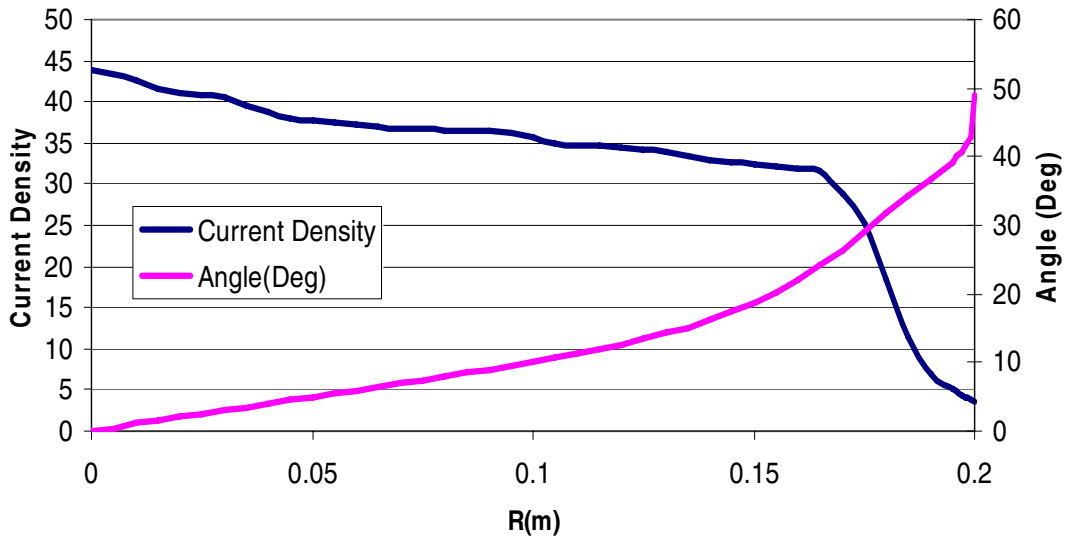

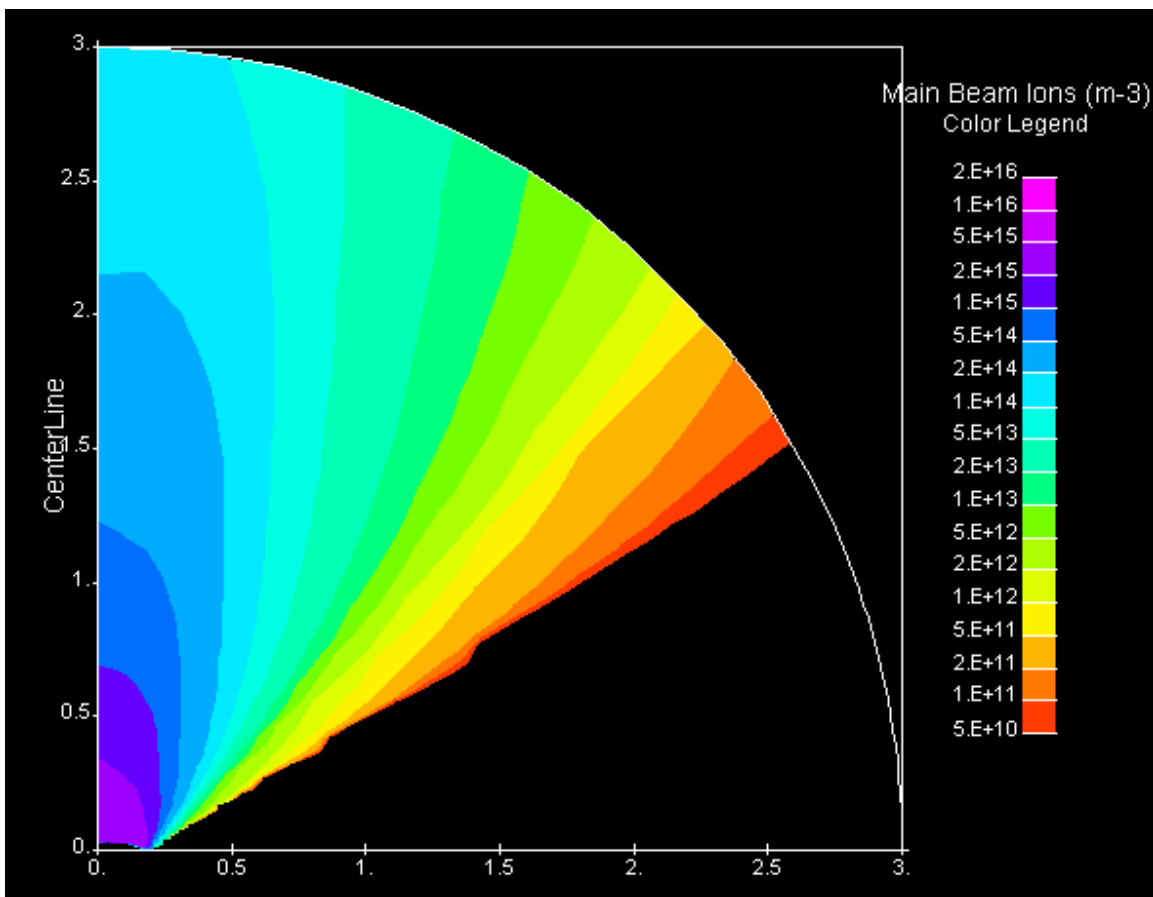**Figure 1. Current density profile and initial angles used as initial conditions for the NEXT calculations.**

Figure 2. Main beam ion density for the NEXT thruster, calculated using *PlumeTool*.

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C. Multiple Thruster Geometric Model

The geometric model for the thruster array is shown in Figure 3. The three active thrusters, along with the dummy thruster, form a square array with 32 cm center-to-center distance between adjacent thrusters. The accel grids and plasma screens are independently biasable. In these calculations the aluminum sides and plasma screens (gold rings around the grids) are grounded. Neutralizers (titanium) are located on each active engine at the point furthest from the center of the array. The neutralizer on the dummy thruster has been omitted from the calculation.

The thruster array is centered on an aluminum square, grounded plate near one end of the computational space. The computational space, whose walls are grounded representing the vacuum tank, is 20 meters long with a 6.7 meter square cross-section. The computational grid resolution ranges from 67 cm near the tank walls to 2 cm near the active thruster grids.
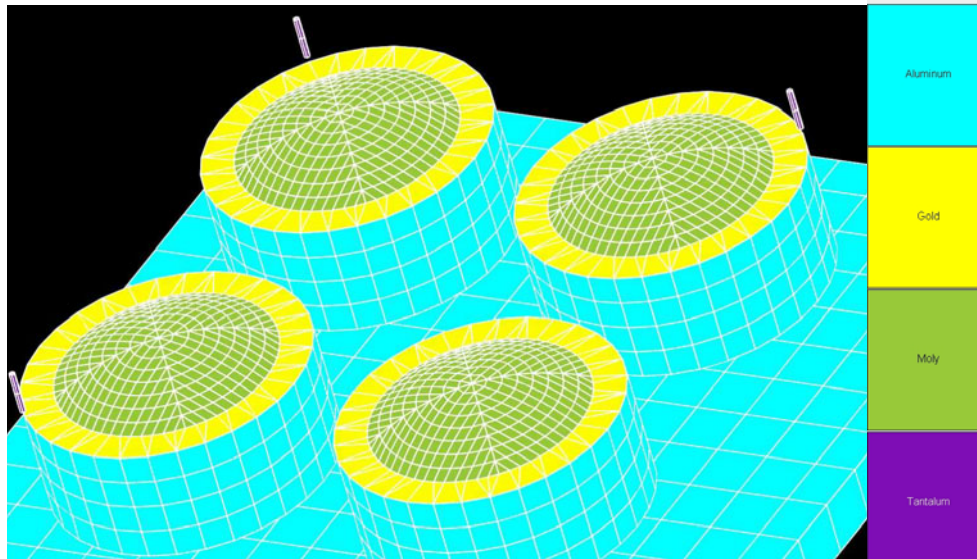

Figure 3. Geometric model of three active NEXT thrusters (plus a dummy) used in calculations.

D. Modeling Inputs

Additional model inputs appear in Table 1. Parameters used in simulation.. The ambient plasma density and the ambient neutral density were taken as optimistically low in order to facilitate the calculation. The electron temperature is set to 1 eV, and electrons are modeled as an isothermal fluid. Other values derive from the published operating parameters of the NEXT thruster[5] or are standard values.

Table 1. Parameters used in simulation.

Parameter	Value
Electron Temperature	1 eV
Ambient Plasma Density	1×10^{12} m^{-3}
Ambient Neutral Density	1×10^{-6} torr = 3.5×10^{16} m^{-3}
Beam Energy	1.8 keV
Beam Current	3.8 Amperes
Thruster Neutral Efflux	0.4 Amperes = 2.4×10^{18} s^{-1}
Neutralizer Neutral Efflux	5.16 sccm = 2.3×10^{18} s^{-1}
Charge Exchange Cross-Section	50×10^{-20} m^2

E. Preliminary Modeling Results

Figure 4 shows the potentials of the superposed plumes of the three active thrusters on a plane through the center of two of the thrusters. This is used as an initial condition for the calculations, and also serves as a point of comparison to note thruster interaction effects. Except immediately adjacent to biased surfaces, the potentials are barometric, *i.e.*, approximately logarithmic with the ion density.

Figure 5 shows the potentials on the same plane as in Figure 4, after calculating the self-consistent potentials by generating and tracking charge exchange ions in the potentials and recomputing potentials until a self-consistent solution is reached. Differences of note between the self-consistent potentials (Figure 5) and the superposed potentials (Figure 4) include:
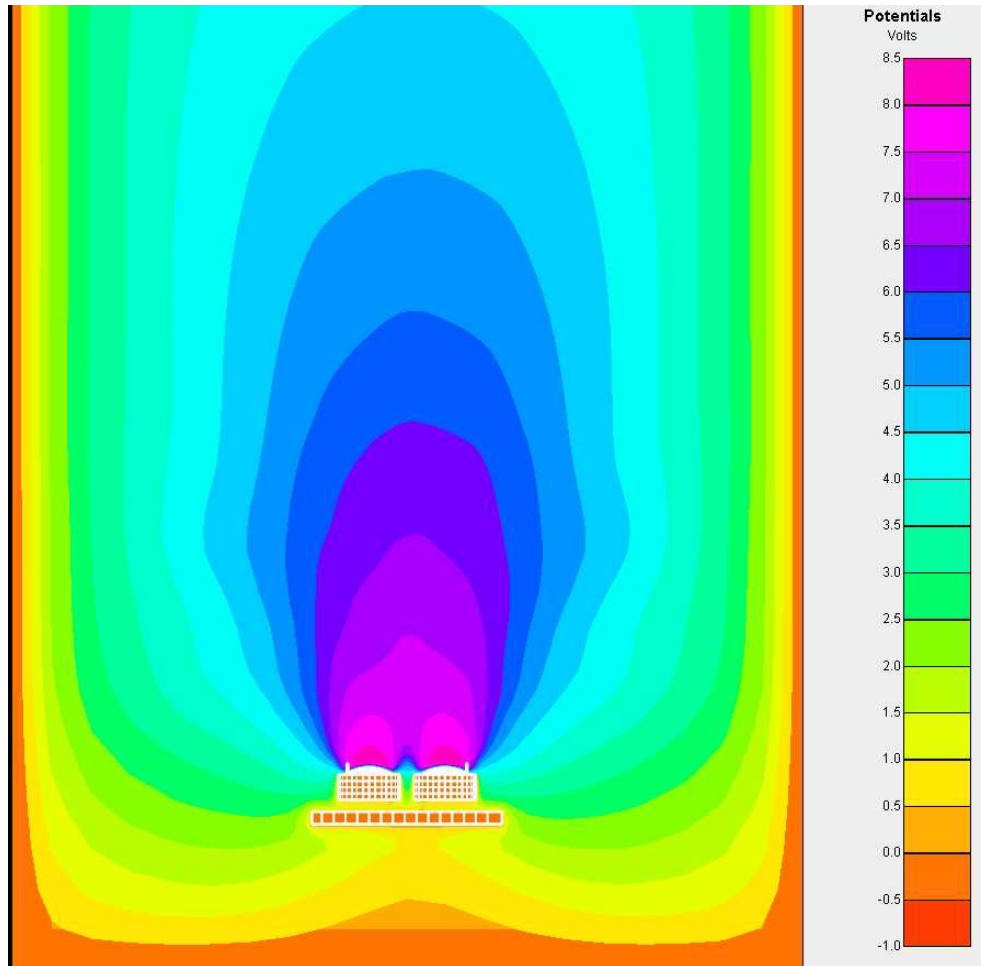
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Figure 4.   Potentials of superposed plumes, used as initial conditions for the calculations.

1. Treatment of the blockage of ions by the thrusters and backing plate. The blockage of ions by the thrusters and backing plate is not included when the plumes were initially generated and superposed, resulting in substantial charge exchange ion density behind the blocking plate. The self-consistent calculation shows low ion density behind the plate and a sensible potential and density structure at the edge of the plate.
2. A charge exchange ion stagnation region occurs about one thruster diameter above the midpoint between the two thrusters. In the superposed plume structure, charge exchange ions are accelerated laterally out of one plume and pass unphysically through the neighboring plume, whereas in the self-consistent structure ions are blocked by the positive potentials of the neighboring plume.
3. The downstream potentials and densities are higher in the self-consistent plume than in the superposed plume, probably because of inhibition of lateral motion by neighboring plumes.

Figure 6 shows self-consistent potentials in the plane of one active and one dummy thruster. As the plume propagates downstream from the active thruster, it appears to move centerward as it merges with the plumes of the other two active thrusters. Also, the potentials indicate flow of charge exchange ions over the dummy thruster.

Figure 7 shows the charge exchange ion densities in the same plane as Figure 5, this time showing the full length of the computational space. The charge exchange ion density is high for a couple of thruster diameters above the array, and exhibits rapid lateral falloff. Beyond a few thruster diameters the density decay is slow both laterally and downstream.

Figure 8 shows the charge exchange ion density in a plane passing through two active neutralizer tips. The neutralizers are modeled as sources of neutrals, which undergo charge exchange with ions at the edge of the main
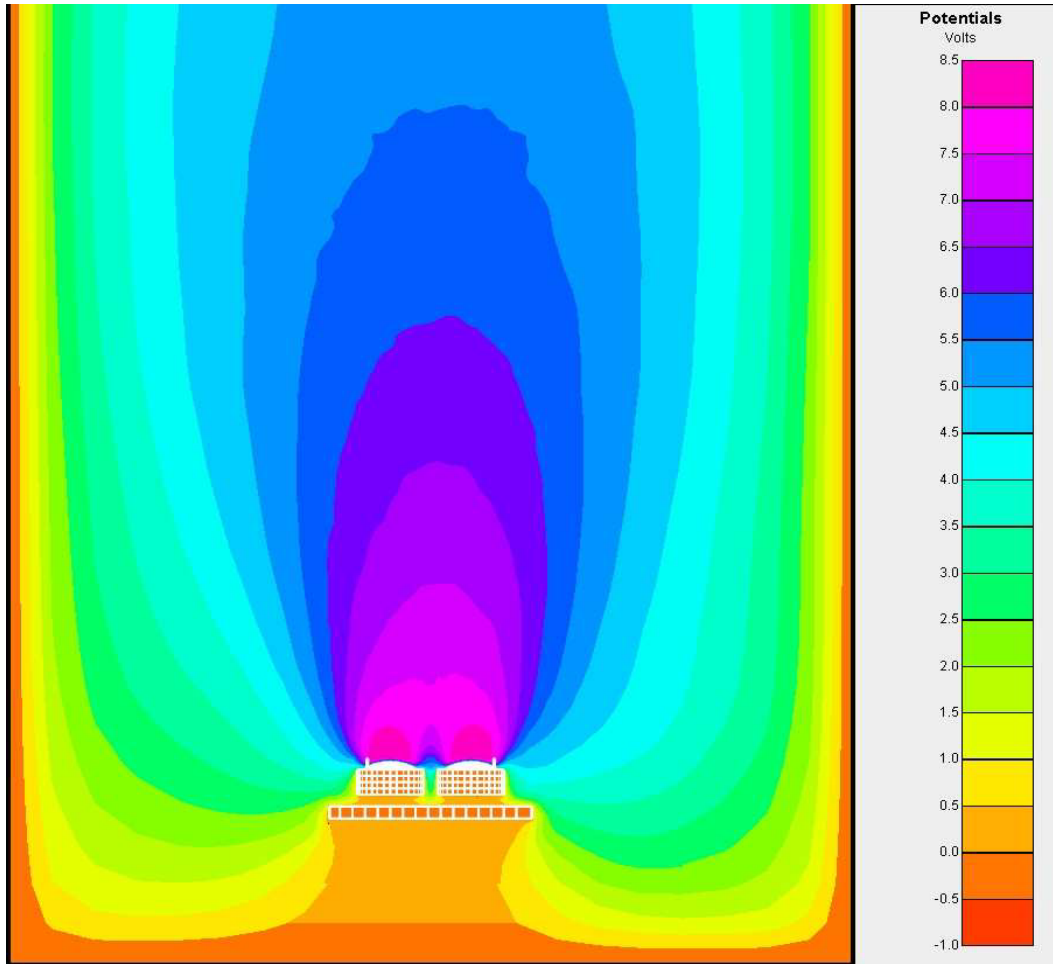
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Figure 5. Results for the potentials in the plumes of the thruster array. (Half of chamber length is shown.) Contours are in a plane through the center of two active thrusters. Potential and density is biased toward the right due to the dummy thruster at the left rear.

beam. Thus, charge exchange ions associated with the neutralizer are create inboard and downstream from the neutralizer (where the beam current is higher) and are accelerated outward past the neutralizer.

Figure 9 shows the distribution of charge exchange ion current on the accel grids, plasma screens, and backing plate. As expected, the charge exchange ion current is highest on the accel grids of the active thrusters. The distribution of current around the plasma screens shows some interesting features. For the three active thrusters the current density is low (~10 mA/m^2) on the portions of the accel grid facing outward from the array center, except for the areas under the neutralizers (40-70 mA/m^2). For the upper right and lower left thrusters, high current densities (~90 mA/m^2) occur in the part of the plasma screen facing between the array center and the nearby active thruster. The current density peak on the center-facing portion of the upper left thruster is lower (~70 mA/m^2) as the charge exchange ions are channeled to flow over the dummy thruster (lower right). Current density to the dummy thruster varies fairly smoothly from ~80 mA/m^2 at the center-facing part to ~20 mA/m^2 on the outboard plasma screen, with a trough on the shadowed portion of the accel grid at lower right.

The accel grid of the dummy thruster can be biased. However, our calculations indicate only a modest increase in current with negative bias (Table 2) due to the thin sheath that forms in the dense charge exchange plasma.

Table 2. Charge exchange ion current collected by biased dummy accel grid.

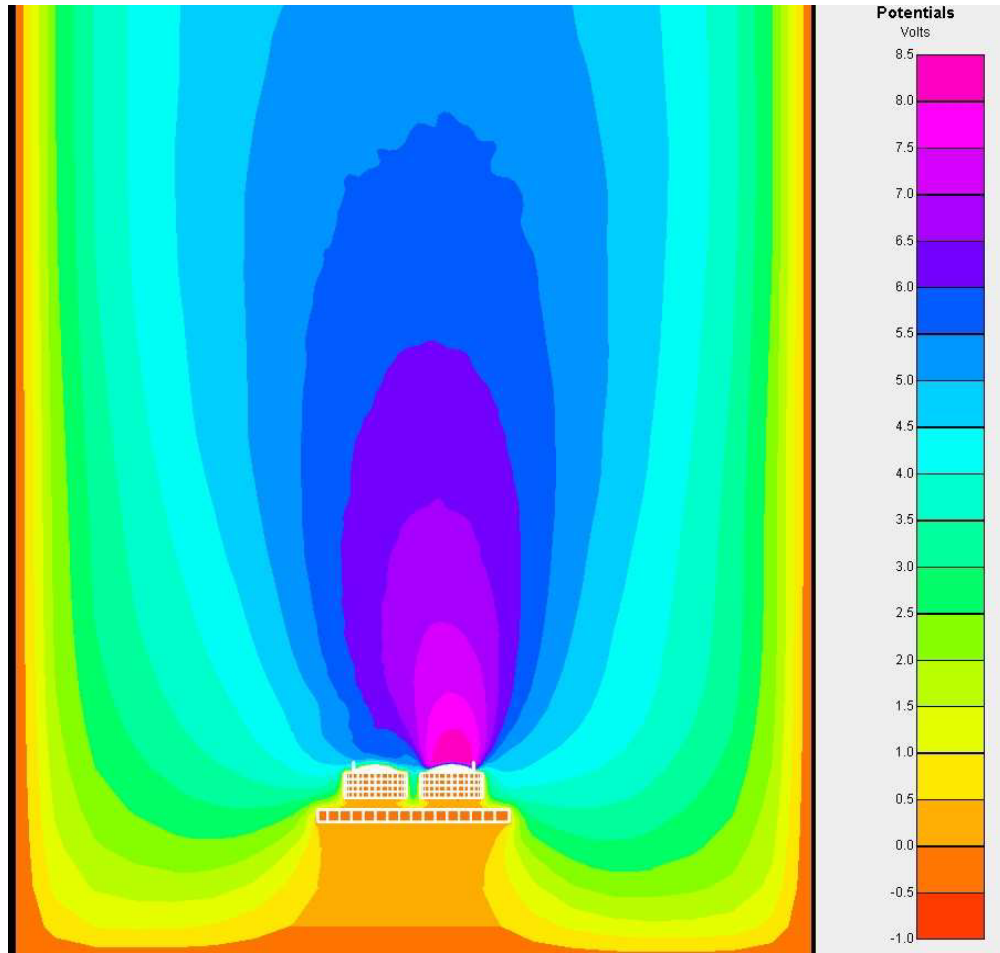| Dummy Accel Grid Bias	Collected Current
0 V	5.4 mA
-10 V	6.4 mA
-50 V	8.1 mA
-250 V	10.5 mA

Figure 6. Potential contours in the plane of one active thruster (right) and one dummy thruster (left).

IV.   Conclusion

We have shown calculations of potentials, charge exchange ion densities, and charge exchange ion currents produced by multiple ion engines. The calculations are fully three-dimensional, and include the presence of biased object surfaces as well as plume interactions. They are performed in modest amounts of time (typically several minutes to about one hour) using the *Nascap-2k* computer code running on standard Windows computers. Though we have not shown examples here, the code is also capable of displaying trajectories of selected test particles for diagnostic purposes.

The results show some definite differences between the self-consistent solution and simple superposition of axisymmetric plumes. One such difference is the stagnation of charge exchange ions between thrusters, which may be of help in operating with less than one neutralizer per engine.

The ground tests to be conducted at NASA Glenn Research Center will help to determine the adequacy of some of the assumptions and simplifications built into these calculations. In particular, we have treated the electrons as an isothermal fluid, and we have treated the neutralizer as just a source of neutrals. Both of these are deserving of far more complex treatment. Analysis of the test results will help us develop better treatments of these factors suitable for use within the *Nascap-2k* framework.
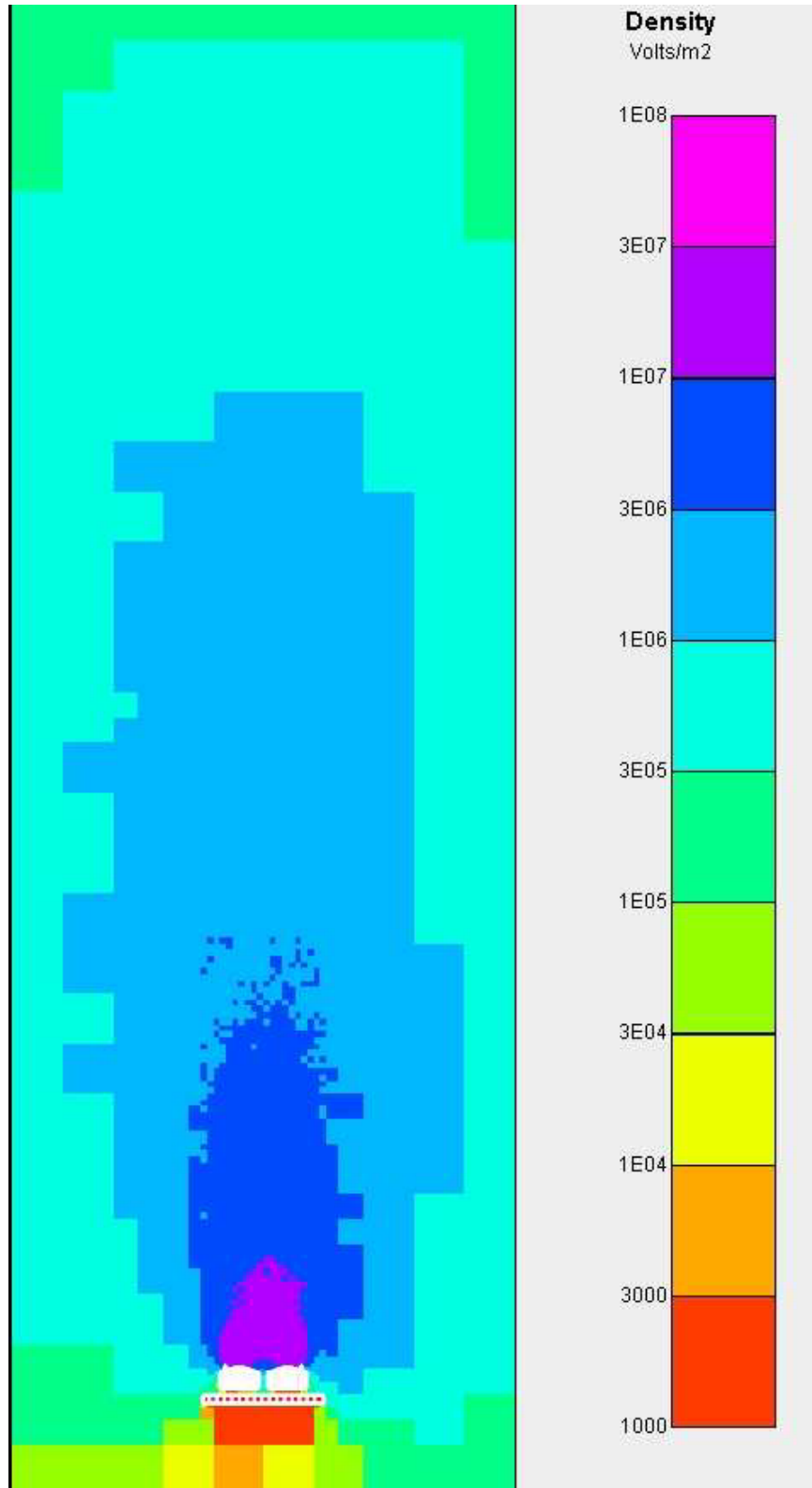
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Figure 7. Charge exchange ion density in a plane through the center of two active thrusters. (To convert units to m^{-3}, multiply by $\varepsilon_0/e = 5.5\times10^7$ V^{-1}m^{-1}.)
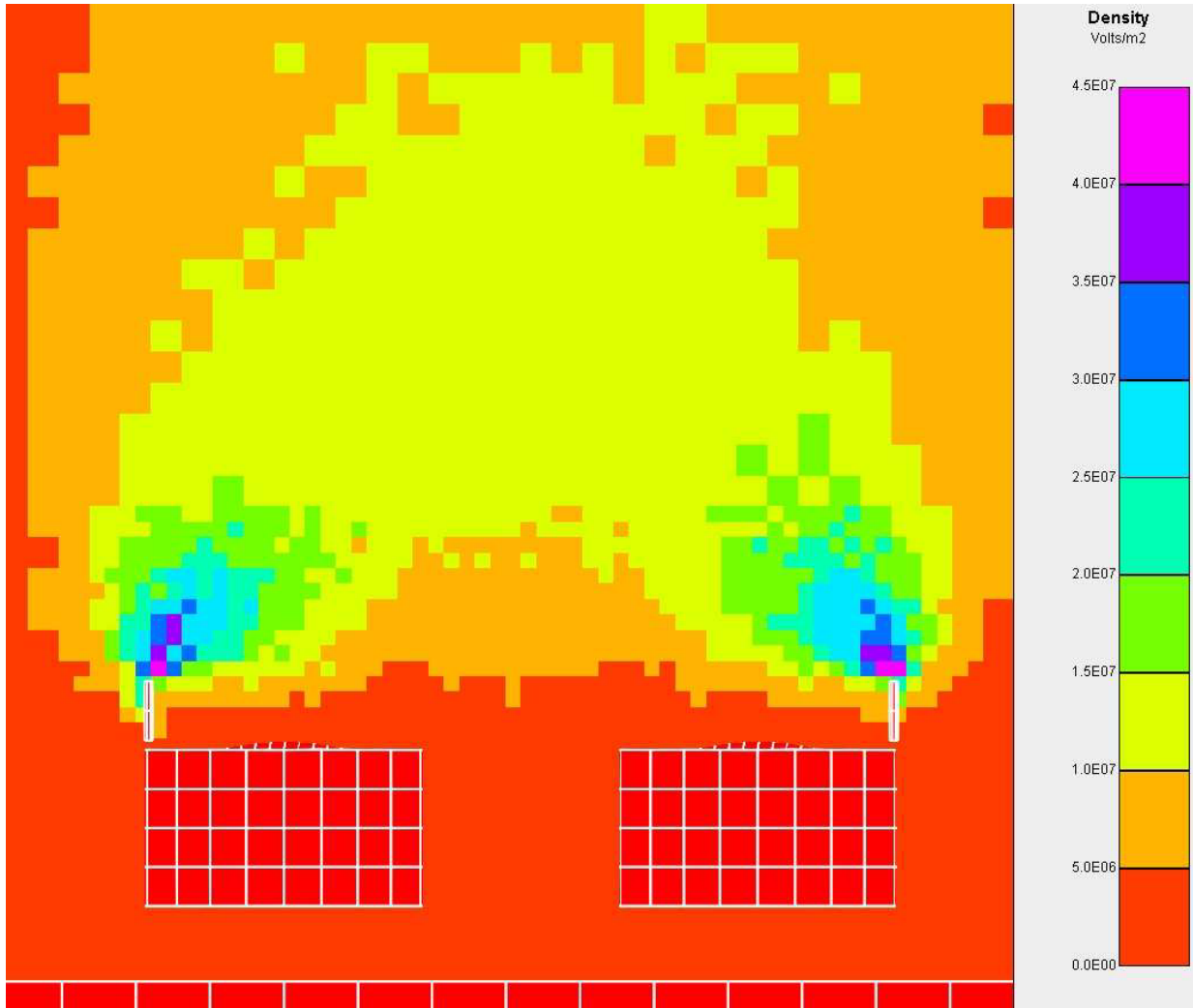
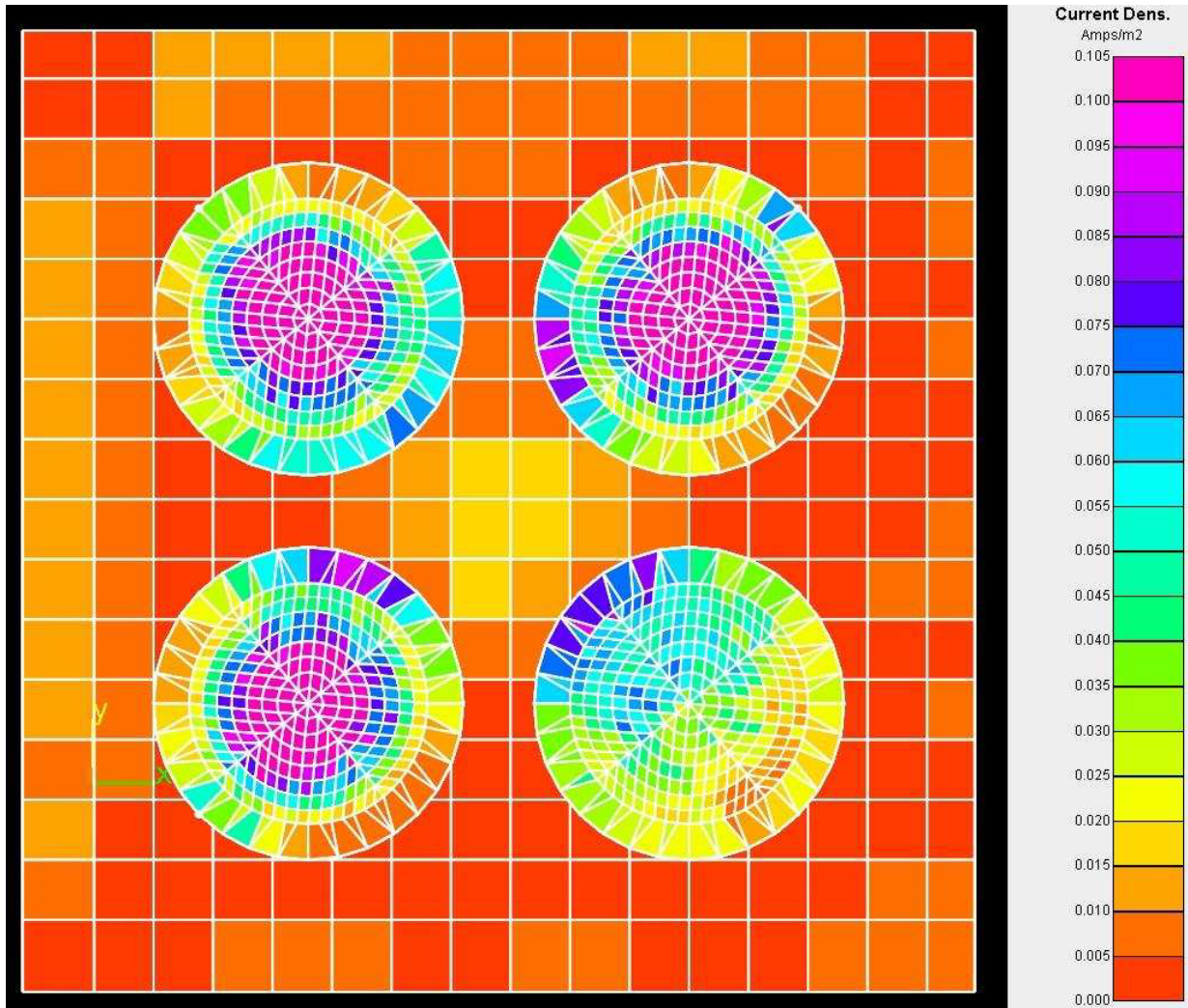**Figure 8. Charge exchange ion density in plane passing through two active neutralizer tips.**

Figure 9. Current density to the grids and plasma shields of the three active thrusters and the dummy (lower right). (Dummy accel grid is grounded.)

References

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[2] Kuharski, R. A., M. J. Mandell, B. M. Gardner, I. Katz and D. Vaughan, "Ion Engine Neutralizer Erosion in Lab and Space," AIAA 2005-3880, 41st AIAA/ASMA/SAI/ASEE Joint Propulsion Conference and Exhibit, 10-13 July 2005, Tucson, Arizona.

[3] Brophy, J. R., I. Katz, J. E. Polk, J. R. Anderson, "Numerical Simulations of Ion Thruster Accelerator Grid Erosion," AIAA-2002-4261, 2002.

[4] Mikellides, I. G., Kuharski, R. A., Mandell, M. J., Gardner, B. M., "Assessment of Spacecraft Systems Integration Using The Electric Propulsion Interactions Code (*EPIC*)," AIAA-2002-3667, 2002.

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