# Backflow Contamination of Indium Liquid-Metal Ion Emitters (LMIE): Numerical Simulations

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## Abstract

A three-dimensional numerical model was developed to investigate the interaction of the ion beam with the neutral efflux of an indium Field-Emission-Electric-Propulsion (In-FEEP) thruster. In a hybrid particle simulation the potential and ion and neutral densities around the thruster are predicted. Two different sources of backflow particles are considered: backsputtered neutrals from weakly charged microdroplets and slow charge-exchange ions which are repelled by space charge potentials and flow back to the spacecraft surface. The backflow distribution from both sources is very different. The sputter current to the spacecraft surface (within 1 mm around the emitter tip) is in the order of $3x10^{-6}$ monolayers/sec, many orders of magnitude higher than the charge exchange current creating a maximum of $3x10^{-14}$ monolayers/sec (distributed within 1 cm around the emitter tip) at an emission current of 50 μA. Both sources are mostly influenced by the emission current. The issue of possible contamination of spacecraft surfaces due to backflow particles is assessed.

## Nomenclature

| | |
|---|---|
| $A_{Liquid}$ | Area of the Taylor Cone [$m^2$] |
| $A_i$, $A_{th}$, $A_{dr}$ | Exit Area of the Ion, Thermal Neutral, and Microdroplet Beam [$m^2$] |
| a | Emitter-Accelerator Distance [m] |
| E | Electric Field [$Vm^{-1}$] |
| e | Electric Charge = $1.602x10^{-19}$ C |
| $\varepsilon_0$ | Electric Constant = $8.854x10^{-12}$ $Fm^{-1}$ |
| $\eta$ | Efficiency [%] |
| $\vartheta_{dr}$ | Microdroplet Divergence Angle [°] |
| $\vartheta_i$ | Ion Divergence Angle [°] |
| $I_i$ | Ion Current [A] |
| k | Boltzmann Constant = 1.381E-23 $JK^{-1}$ |
| $m_i$ | Ion Mass [kg] |
| N | Number of Particles [#] |
| $n_i$, $n_n$, $n_{th}$ | Ion, Neutral, and Thermal Neutral Number Density [$m^{-3}$] |
| p | Vapor Pressure [Pa] |
| $\rho$ | Charge Density [$Cm^{-3}$] |
| r | Inner Accelerator Radius [m] |
| $r_{ACC}$ | Outer Accelerator Radius [m] |
| $r_{dr}$ | Radius of Microdroplet [m] |
| $r_E$ | Radius of Emitter Needle [m] |
| $\sigma_{CEX}$ | Charge-Exchange Cross Section [$m^{-2}$] |
| $\sigma_{sp}$ | Neutral Sputter Cross Section [$m^{-2}$] |
| T | Temperature [K] |
| $U_E$ | Emitter Potential [V] |
| $U_{Exit}$ | Potential in Exit Area of Emitter [V] |
| $v_i$, $v_{th}$, $v_{dr}$ | Ion, Thermal Neutral, and Microdroplet Velocity [$ms^{-1}$] |
| Y | Sputter Yield Coeffiencient [m] |
| $\phi$ | Potential [V] |

## 1. Introduction

Indium Liquid-Metal-Ion-Emitters (LMIE) are an advanced electrostatic propulsion concept which uses liquid metal as a propellant. A LMIE device consists of an emitter and an accelerator electrode. Two different designs have been developed under ESA contracts. One design by CENTROSPAZIO uses cesium in a slit emitter and negative accelerator potentials with respect to the spacecraft surface potential, whereas the Seibersdorf LMIE uses indium in a needle emitter and an accelerator electrode which is on the same potential as the spacecraft surface. While the CENTROSPAZIO type of emitter has been successfully modeled previously[1,2], the present paper concentrates on simulating the Seibersdorf type of LMIE emitter.

A potential difference of several kV is applied between the emitter and the accelerator electrode, which generates a strong electric field and forms a Taylor cone on the liquid metal surface of the emitter. This electric field extracts indium ions from the tip of the emitter and accelerates them through the accelerator. Due to the high emitter-accelerator potential difference, the propellant ions are accelerated to a very high velocity, typically > $10^5$ m/s. Hence, a LMIE device can produce specific impulses on the order of $10^4$ s.

A three-dimensional hybrid Particle-In-Cell (PIC) simulation using volumetric collisions is developed for simulation of an indium Liquid-Metal-Ion-Emitter (LMIE). In addition to ions, all field emission sources emit weakly charged microdroplets,

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their number depending on the emitted current[3]. The simulation model is used to predict the neutral atoms resulting from sputtering between the micro-droplets and the ion beam. Moreover, charge-exchange collisions between the ion and the sputtered neutral particles are performed to study slow ions which move along the electric fields created by the emitter potentials and the ion beam's space charge. Eventually, such particles will hit the spacecraft and therefore are a potential source of contamination. No dedicated measurements exist to characterize this contamination problem. Computer simulations provide the best means to initially characterize this issue and to estimate the possible contamination.

The main objective of this paper is to investigate the backflow contamination due to sputter neutrals and charge-exchange ions. After the development of the numerical and sputter model, 3D spatial distributions and backflow currents are evaluated and discussed.

## 2. Physical Model

### 2.1 Ion Model

In a LMIE, ion emission originates from a Taylor cone located at a distance $a$ (emitter-accelerator distance) below the accelerator electrode [Figure 1]. Typically, the accelerator electrode of the LMIE emitter is part of the outer spacecraft surface. The accelerator is near the spacecraft potential, the emitter on a positive potential (≈ +6 kV) with respect to the spacecraft. The geometry of the electrodes creates a focused ion beam which is then accelerated through the accelerator. The velocity of the beam ions at the emitter's exit, $v_i$, is given by

$$v_i = \sqrt{\frac{2\cdot(U_E - U_{Exit})\cdot e}{m_i}} \tag{1}$$

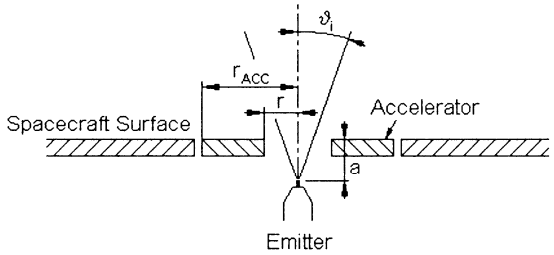


**Figure 1 LMIE Emitter Model**

where $U_E$ is the emitter potential and $U_{Exit}$ the potential within the ion beam at the accelerator electrode. Note $U_{Exit}$ is not exactly the spacecraft surface potential (we assume it is 0 Volt with respect to infinity), rather it is a variable which needs to be determined self-consistently by taking the space charge into account. At the emitter's exit, to a good approximation, the propellant ions are focused into a "squeezed" cosine distribution[3]. If the ions were perfectly neutralized and there were no space charge effects, they would form a beam with a divergence angle of $\vartheta_i$. Under this condition, the cross section of the ion beam near the emitter's exit would be

$$A_i = (a\cdot\tan\vartheta_i)^2\cdot\pi \tag{2}$$

The corresponding exit density $n_i$ can be expressed by the ion current $I_i$

$$n_i = \frac{I_i}{e\cdot v_i\cdot A_i} \tag{3}$$

### 2.2 Neutral Model

The neutral flux emitted by the LMIE consists of 1.) thermal neutrals which are vaporized from the free liquid-metal surface inside the emitter needle according to its temperature and 2.) a component which is emitted during field emission. This second component mostly consists of microdroplets with an average diameter of $5\text{x}10^{-8}$ m. These droplets have a small charge which determines their velocity which can be calculated for the present type of emitter[3] and is $v_{droplet}$=1440 $\text{ms}^{-1}$. To a good approximation, the droplets are also focused into a "squeezed" cosine distribution[3] similar to the beam ions with a slightly larger divergence angle $\vartheta_{dr}$.

Because we are interested in the backflow contamination due to charge-exchange collisions which create slow ions that are attracted by space charge and surface potentials, we have to model neutral indium atoms which collide with the fast beam ions. The thermal vaporization creates neutral atoms where the density can be expressed by

$$n_{th}(z) = \frac{p}{\sqrt{2\pi mkT}}\cdot A_{Liquid}\cdot\frac{1}{v_{th}\cdot A_{th}(z)} \tag{4}$$

where $p$ is the vapor pressure of indium depending on the temperature $T$ (the operating temperature $T$=473 K and therefore $p$=$5\text{x}10^{-11}$ Pa from Honig et al[4]), $k$ the Boltzmann constant, $m$ the atomic mass of indium ($m$=$2.2\text{x}10^{-25}$ kg), $A_{Liquid}$ the area of the free liquid metal surface, $v_{th}$ the thermal velocity, and $A_{th}(z)$ the thermal beam cross section at the distance $z$ from the emitter needle.

The free liquid metal surface $A_{Liquid}$ is calculated from the area of the Taylor cone which forms an angle of 90° over the base from the needle exit with the radius $r_E$

$$A_{Liquid} = r_E^2\cdot 1.4213\cdot\pi \tag{5}$$

The temperature results in a Maxwell-Boltzmann distribution and therefore to a mean thermal velocity $v_{th}$

$$v_{th} = \sqrt{\frac{8kT}{m\pi}} \tag{6}$$

In this model, the thermal neutrals flow from a single point source which effuse through a hole of the inner accelerator radius $r$ where the area of the beam depending on its distance $z$ can be described by Bird[5]

$$A_{th}(z) = \frac{2 \cdot r^2 \cdot \pi}{\left[1 - \left\{1 + \left(\frac{r}{z}\right)^2\right\}^{-1/2}\right]} \tag{7}$$

If we compare the exit density from the ion beam, with a typical example at a current of $I_i$=250 A, with the assumption of $U_{Exit}$=0V, $U_E$=6 kV, and $r_{ACC}$=1 mm which results in $n_i$=5.3x10$^{15}$ m$^{-3}$ with the neutral exit density using $a$=0.7 mm and $r_E$=0.2 mm which results in $n_{th}(a)$=1x10$^8$ m$^{-3}$, we note that the difference is more than 7 magnitudes. This would result in a neglectible amount of charge-exchange collisions. However, mass spectroscopic measurements for the CENTROSPACE type of emitter indicated a density of neutral atoms comparable to the ion beam density[2,6]. It has been suggested, that this is due to the dissociation of the microdroplets under the influence of the strong electric fields[6,7]. However, one microdroplet consists of 8x10$^6$ indium atoms and the abundance of neutral atoms must therefore results from 8x10$^6$ dissociations down to the atomic level which is very unlikely.

A physically more plausible explanation is, that the neutral atoms result from sputtering of microdroplets by fast beam ions. The number of sputtered neutral atoms per second at a distance $z$ from the emitter needle in a volume with a depth of $dz$ can be expressed by

$$\dot{N}_{sp} = \frac{\dot{N}_i \cdot \dot{N}_{dr} \cdot \sigma_{sp} \cdot Y \cdot dz}{A_i(z) \cdot v_{dr}} = \frac{\left(\frac{I_i}{e}\right) \cdot \left[\frac{I_i}{e} \cdot \left(\frac{1}{\eta} - 1\right) \cdot \frac{m}{m_{dr}}\right] \cdot r_{dr}^2 \cdot \pi \cdot Y \cdot dz}{A_i(z) \cdot v_{dr}} \tag{8}$$

where $dN_i/dt$ is the number of ions emitted per second, $dN_{dr}/dt$ the number of microdroplets emitted per second, $\sigma_{sp}$ the sputter cross section, $Y$ the sputter yield coefficient (for indium $Y$=10), $dz$ the height of the volume in which the sputter particles are created, $\eta$ the emitter's efficiency, $r_{dr}$ the droplet radius, and $A_i(z)$ the ion beam cross section which can be expressed by

$$A_i(z) = (z \cdot \tan \vartheta_i)^2 \cdot \pi \tag{9}$$

The sputter particles are always backscattered in a cosine distribution perpendicular to the point of impact on the surface of the microdroplet. The mean sputter energy[3] is 10 eV. This creates a considerable number of neutral atoms which may explain the source of the observed neutral flux during field emission. However, this hypothesis has to be confirmed by measurements.

In this study, only the neutral atoms resulting from the thermal vaporization and the atoms due to sputtering between the fast beam ions and the microdroplets are simulated.

### 2.3 Charge-Exchange Collision Model

We will only concentrate on the resonant charge transfer mechanism because it has the highest cross section. These collisions exchange the momentum between both collision partners. This means, when a fast ion collides with a slow neutral, the collision produces a fast neutral and a slow ion:

$$In^+_{fast} + In^0_{slow} \rightarrow In^+_{slow} + In^0_{fast} \tag{10}$$

From the quantum-mechanical theory of collisions, the velocity dependent resonant charge exchange cross section $\sigma_{cex}$ can be expressed as[8]:

$$\sigma_{cex}^{1/2} = k_1 \ln v + k_2 \tag{11}$$

where $v$ is the relative velocity between the ions and the neutrals. Unfortunately, In-In+ resonant charge exchange measurements are not available. But because the curves are very similar and mainly depend on the ionization potential, the values of lithium have been used in this study which has the closest ionization potential to indium. The values[9] are $k_1$= -1,599x10$^{-10}$ s and $k_2$= 2,884x10$^{-9}$ m.

## 3. Numerical Implementation

A hybrid three-dimensional electrostatic Particle-In-Cell (PIC) code[10] has been developed to study LMIE-induced plasma interactions. In this code, all particles (beam ions, charge-exchange ions, sputter neutrals) are treated as computational test particles whereas the microdroplets are modeled as a fluid. The trajectories of each test particle, the space charge and the self-consistent electric field are obtained from Newton's second law and Poisson's equation.

The emitter is located in the middle of the bottom simulation domain. Test particles representing the beam ions are injected into the simulation domain over the needle tip on the spacecraft surface with the velocity $v_i$ [Equ 1]. At the start of the simulation, the beam ions follow the spatial distribution given by Equ (2). The thermal neutral atoms density is assigned to the grid using Equ (4). At each time step, volumetric sputter and charge-exchange collisions are performed and the corresponding number of test particles is created on each gridnode.

A Neumann boundary condition for Poisson's equation is applied on all open boundaries, while the potentials at the surfaces of the spacecraft box, the emitter, accelerator, and neutralizer are specified.

The size of the simulation domain was 0.02x0.02x0.02 m and the number of grid cells was 20x20x20. Similar to previous models[1,2], all simulation parameters were varied to ensure that they do not effect the equilibrium situation. The timestep was based on the electron plasma frequency. The simulation was performed until an equilibrium was reached, i.e. the number of particles in the simulation domain remained constant. In a typical case, the number of particles at equilibrium was 80,000 and the number of timesteps to reach equilibrium was 30,000. A typical run takes about 3-4 days on a Silicon Graphics Power Challange XL computer.

The 3-D simulation code has been tested against the ion density measurements obtained for a cesium LMIE emitter at CENTROSPAZIO[2]. The results show a very good agreement between simulations and measurements.

### 3.1 Sputter Collisions

The number of sputter particles generated at each time step *dt* at a given distance z from the needle tip is given by Equ (8). In this case, *dz* is the height of the grid cells in z-direction and therefore determines the resolution of the volume. To calculate the number of computer particles per second at each gridpoint in the volume *dx.dy.dz* at the distance *z* from the needle tip, the total amount has to be multiplied by the ratio of the area covered by one gridpoint, which can be approximated by *dx.dy*, to the total area of sputter cross section which is $A_i(z)$:

$$\dot{N}_{sp,\text{gridpoint}}(z) = \dot{N}_{sp}(z) \cdot \frac{dx \cdot dy}{A_i(z)} \tag{12}$$

The particles created are initialized with a cosine velocity distribution equivalent to the mean sputter energy[3] of 10 eV perpendicular to the point of impact on the microdroplet which is calculated using the random number $0° <= R_1 <= 360°$, $0° <= R_2 <= 180°$, and $0° <= R_3 <= 180°$ according to Figure 2.

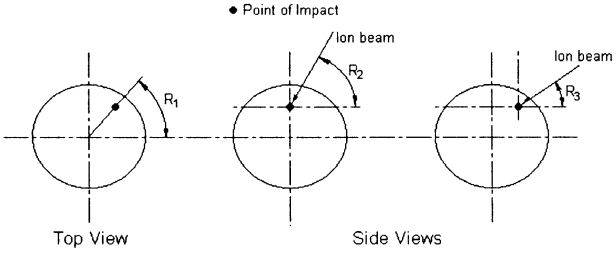


**Figure 2 Sputter Impact Point on the Microdroplet**

### 3.2 Charge-Exchange Collisions

The number of charge-exchange computer particles $N_{CEX}$ created at every time-step *dt* is given by the total neutral density $n_n$ (thermal and sputter neutrals), the beam ion density $n_i$ and the charge-exchange cross section $\sigma_{CEX}$ by

$$\frac{dN_{CEX}}{dt} = n_i n_n v_i \sigma_{CEX}(v_i) \tag{13}$$

where $v_i$ is the ion velocity, neglecting the neutral velocity which is almost 2 orders of magnitude below. The particles move along the electric field lines in the domain which is composed of the surface and space charge potentials.

## 4. Simulation

In the model described above, there are two possible spacecraft contamination hazards which are evaluated in this paper:

1. backscattered neutral sputter contamination,
2. and charge-exchange backflow contamination due to the sputter and thermal neutral atoms environment

The contamination environment is evaluated for a LMIE thruster operating at two typical operation points at 50 μA and 250 μA, the detailed operating conditions are given in Table 1 which are based on experimental data given by Fehringer et al[3], the simulation cases are summarized in Table 2. Emission occurs in a vacuum environment without a neutralizer to study the worst case scenario. Due to low density of the LEO orbit electron density ($10^{12}$ $m^{-3}$) compared to the exit density of the beam ions ($10^{15}$ $m^{-3}$), the vacuum environment is a good assumption to resemble the backflow contamination as expected during the operation in space.

| LMIE Emitter | Parameters |
|---|---|
| Emitter Efficiency | 60 % |
| Needle Radius | 0.2 mm |
| Accelerator Radius | 1 mm |
| Emitter-Accelerator Distance | 0.7 mm |
| Ion Divergence Angle | 50° |
| Microdroplets Divergence Angle | 60° |
| Operating Temperature | 473 K |

**Table 1 LMIE Operating Conditions**

### 4.1 Backscattering Sputter Contamination

We will first evaluate the neutral environment due to sputtering between the microdroplets and the fast beam ions, and thermal neutral emission. The neutral environment is also the basis for the charge-exchange backflow contamination. Because sputter particles have

| Case | Emitter Voltage [kV] | Emitter Current [μA] | CEX Backflow Current $I_B$ [μA] | CEX Backflow Current Lost $I_{B,Lost}$ [μA] | Backscattering Sputter Current $I_{Sp}$ [μA] |
|---|---|---|---|---|---|
| Case 1 | 6 | 50 | 2.19 ± 0.01 E-11 | 3.44 ± 0.06 E-9 | 9.88 ± 0.03 E-6 |
| Case 2 | 7 | 250 | 4.05 ± 0.03 E-9 | 1.77 ± 0.08 E-7 | 2.22 ± 0.01 E-4 |

**Table 2 Spacecraft Contamination Simulation Cases**

a cosine velocity distribution perpendicular to the point of impact which therefore must look towards the ion beam emission on the surface, sputter neutrals can flow back to the spacecraft surface and therefore can contribute to contamination. However, because neutrals are not affected by potentials, the contamination in this case is limited to the surroundings of the LMIE.

The total neutral density for Case 1 on a x-z plot across the middle of LMIE's emitter needle is shown in Figure 3. The backscattering from the sputter neutrals is clearly evident, the cosine velocity distribution moves most of them back to the emitter needle from where the fast ion beam originates. This results in a sputter neutral backflow which can be seen in Figure 5 for Case 1 with a sharp maximum over the emitter needle of $4x10^{-6}$ monolayers/second at an ion current of 50 μA. Actually the backsputtered indium atoms in this maximum almost completely reenter the extraction hole in the accelerator. The rest of the backscattered neutrals is homogeneously distributed around the emitter but nearly 5 orders of magnitude below its maximum. In Case 2, the maximum raises to $1x10^{-4}$ monolayers/second at an ion current of 250 μA being again concentrated over the emitter needle. Figure 4 shows the neutral density due to thermal evaporation from the Taylor cone at the emitter needle. Obviously, this density is smaller comparing to the sputter neutral density being 3 orders of magnitude below. This is due to the very low vapor pressure of indium ($p$=$5x10^{-11}$ Pa from Honig et al[4]) even at the operating temperature of 473 K, assumed to be identical in Cases 1 and 2.

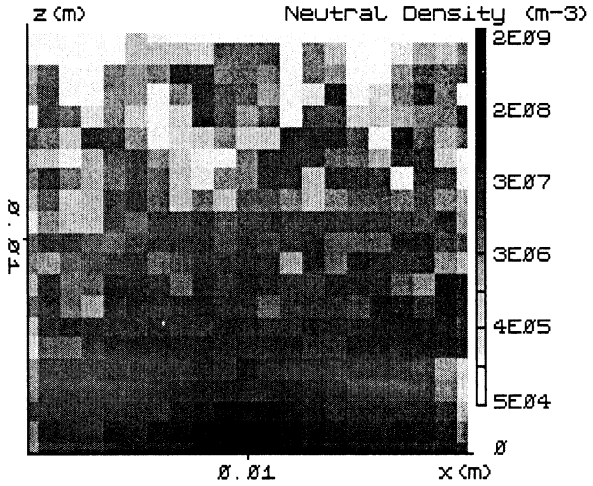


**Figure 3 x-z Plot of Total Neutral Density – Case 1**

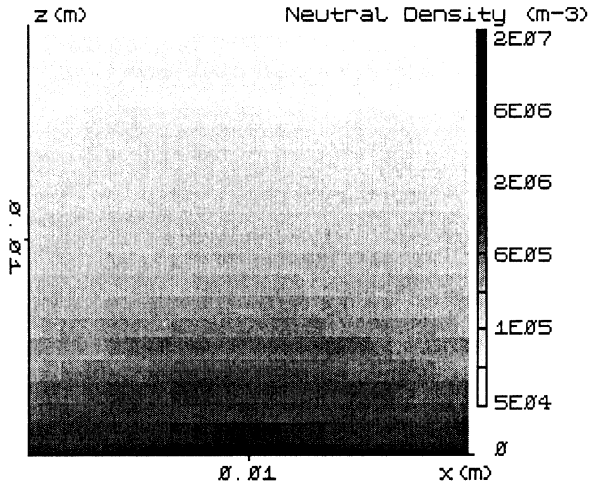


**Figure 4 x-z Plot of Thermal Neutral Density – Case 1 and Case 2**

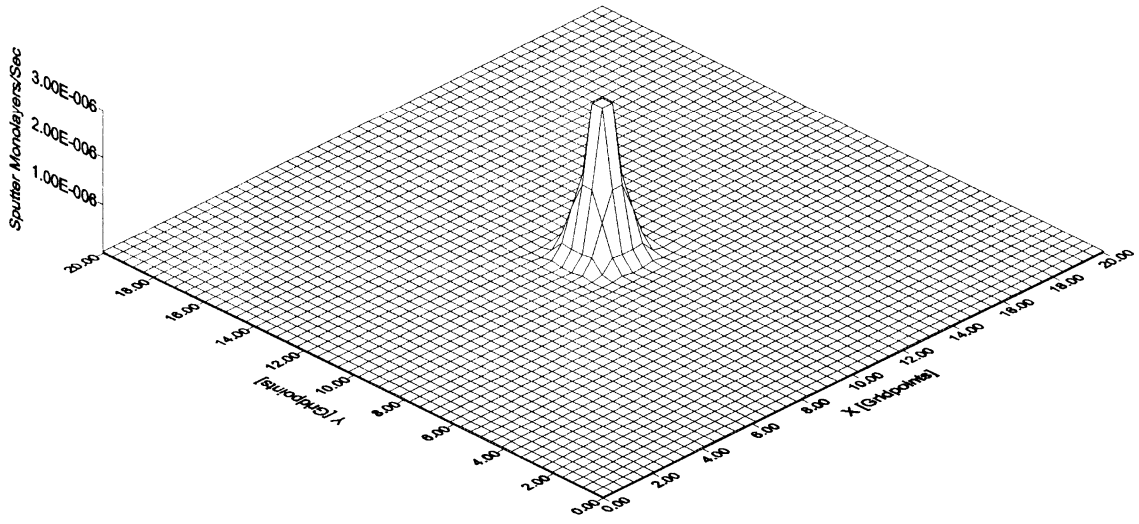


**Figure 5 3D Distribution of Sputter Monolayers/Second on the Spacecraft Surface 0.02x0.02m – Case 1**

The amount of sputter particles created depends on both the microdroplet and the ion density as indicated by Equ (8). Both depend on the ion current $I_i$, therefore it is expected, that the backscattering sputter current $I_{Sp}$ scales with $I_i^2$. The ratio between the sputter currents $I_{Sp}$ for both cases is 22.4 which is close to the square of the ratio of both ion currents which is 25. The slightly lower amount is due to the higher distribution around the emitter. However, the scaling of the sputter current $I_{Sp}$ with the square of the ion current $I_i$ is confirmed.

This behavior is different from measurements with slit emitters using cesium as a propellant. They indicated a linear relationship of the neutral current with the ion current[6]. These measurements were done using a mass spectrometer more than 40 cm above the emitter, which is a very large distance compared to the 2 cm height of the simulation domain. Mass spectroscopy is an invasive measurement technique as well. To prove, if the atomic neutral particles are only due to sputtering, new measurements have to be carried out which have to be closer to the emitter to investigate the new proposed relationship.

### 4.2 Charge-Exchange Backflow Contamination

The neutral environment created by sputtering between the ions and microdroplets and thermal evaporation from the Taylor cone causes charge-exchange (CEX) collisions between the neutrals and the ion beam. This results in slow ions that are attracted by potentials in the simulation domain. The potentials are composed of the positive emitter potential on the surface and the space charge potentials in the domain. The emission occurs in a vacuum environment without a neutralizer, therefore, no negative charges or potentials are present and space charge effects will dominate the charge-exchange characteristics. A positive charge built-up above the emitter can repulse slow ions to move back to the spacecraft surface causing a backflow current and therefore a possible contamination hazard. This hazard is different from the sputter one because it can be attracted by potentials on other parts of the spacecraft and is therefore not limited to the surroundings of the LMIE.

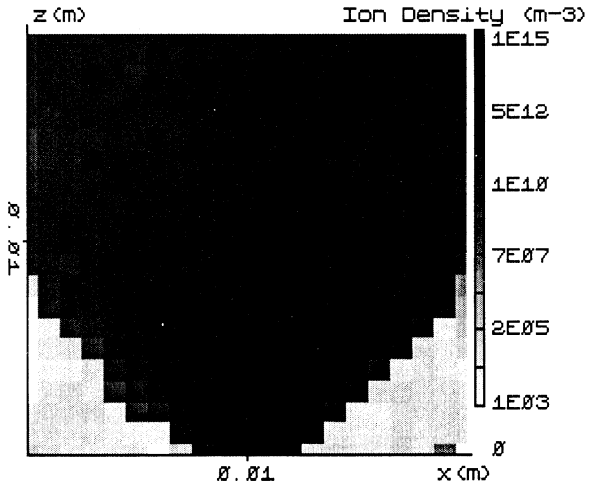


**Figure 6 x-z Plot of Total Ion Density – Case 1**

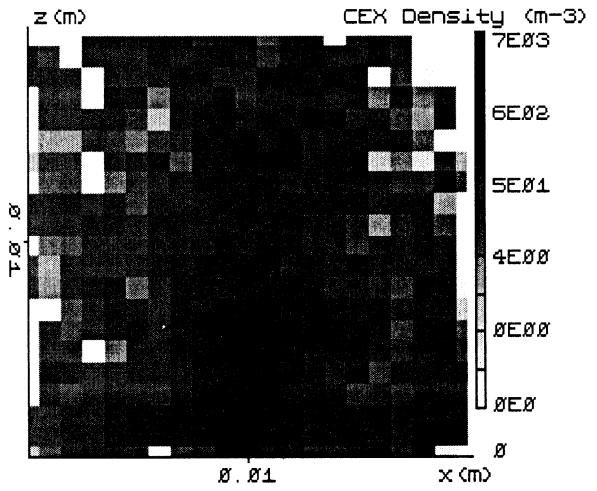


**Figure 7 x-z Plot of Charge-Exchange Ion Density – Case 1 and Case 2**

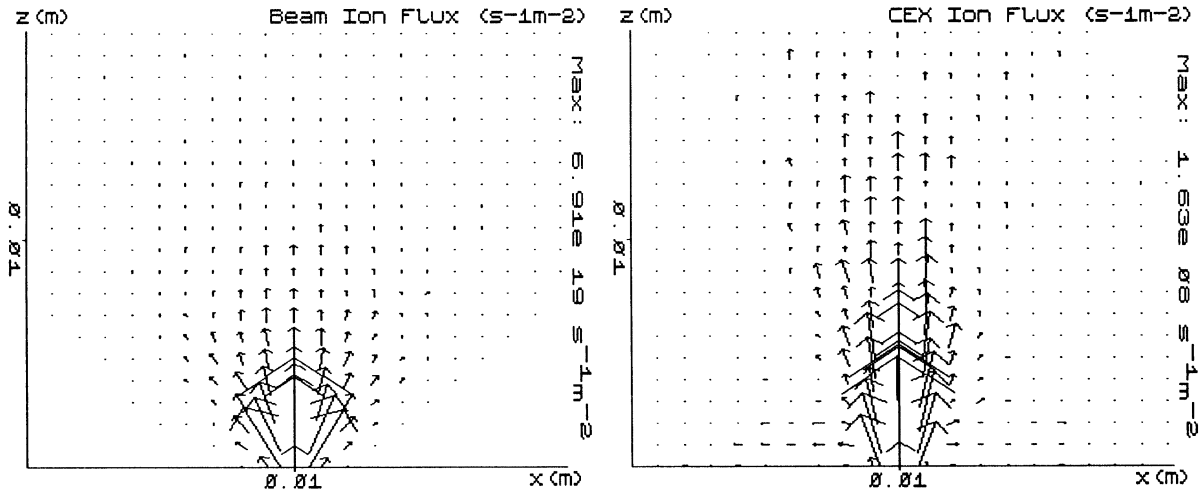


**Figure 8 Beam Ion and CEX Flux $n_i v_i$ - Plot x-z at Plane y=0.05 m – Case 1**

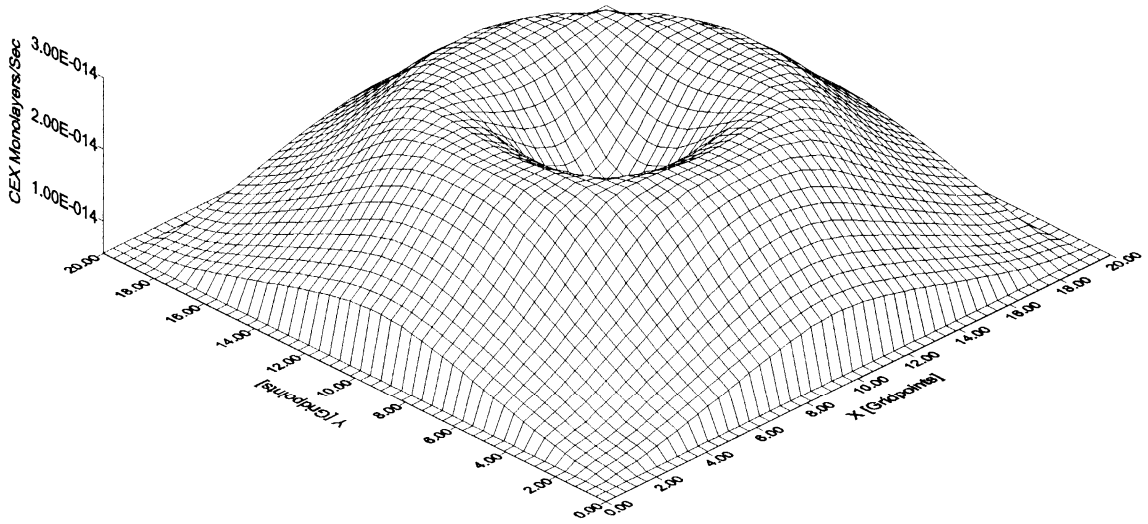


**Figure 9 3D Distribution of Charge-Exchange Monolayers/Second on the Spacecraft Surface 0.02x0.02m – Case 1**

The total ion density, charge-exchange ion density as well as the corresponding beam ion and charge-exchange ion flux vectors are shown in Figure 6, 7, and 8 for Case 1 respectively. Comparing the beam and charge-exchange ion flux in Figure 8, we see the dominance of the high positive emitter potential on the slow ions which creates a much more focused beam. We also note, that ions at the outer boundary of the ion beam are repulsed by the space charge potential which results in a backflow monolayers shown in Figure 9. The positive emitter potential creates a crater around the LMIE which corresponds to the accelerator radius, the rest of the backflow is concentrated in a 1 cm radius around its center.

The integrated backflow current $I_B$ over the spacecraft surface for both cases is given in Table 2. Generally, it is 10 orders of magnitude below the ion current $I_i$ and also several orders of magnitude below the backscattering sputter current $I_{Sp}$. Therefore, it will only play a minor role in spacecraft contamination. Nearly all of the remaining charge-exchange ions are repulsed by the positive emitter and space charge potential away from the spacecraft. Nevertheless, these slow ions can still be a contamination problem for other parts of the spacecraft that can attract them, e.g. areas with high negative potentials.

To evaluate this contamination risk, we can built the ratio $I_B / (I_{B+IB,Lost})$ using the backflow current $I_B$ and the charge-exchange current which is lost through the simulation domain $I_{B,Lost}$ to get the percentage of how much current was collected at the spacecraft surface. Using the values given in Table 2, we get 1% of backflow current collection on the surface for both cases. This value is very small, also the maximum contamination current of $I_B + I_{B,Lost}$ is over 8 magnitudes below the ion current emitted by the LMIE and therefore a very small value.

The amount of charge-exchange collisions depend on the ion and neutral density, the ion density being proportional to the ion current $I_i$ and the neutral density (dominated by the sputtered atoms) being proportional to the square of the ion current $I_i$. Therefore, the backflow current $I_B$ will relate to the 3rd power of the ion current $I_i$. The ratio between the backflow current for both cases is 185 [Table 2] and the ratio between the ion current is 125. The difference is due to the space charge which causes the backflow current to the surface. However, this space charge is small and cannot be solved analytically. For approximations, the scaling factor for the backflow current $I_B$ can be assumed to be proportional to the 3rd power of the ion current $I_i$.

## 5. Conclusions

Additionally to the emission of ions, a LMIE produces a flux of microdroplets. The model accounts for sputtering between these two fluxes which produces a backscattered neutral atom particle flux. This sputter neutral flux is concentrated in a narrow region around the emitter needle from where the ion emission originates and almost completely reenters the LMIE extractor hole. The sputter contamination hazard therefore is limited to the emitter itself. Since the backsputtered atoms are of the same kind as the charge material, this sputter contamination problem is deemed to be of little significance. The sputter neutral current $I_{Sp}$ is proportional to the square of the ion current $I_i$ which is different from previous measurements on a cesium slit emitter which only indicated a linear relationship. They were carried out at a distance of 40 cm which is very large compared to the 2 cm height of the simulation domain. New measurements near the emitter are needed to validate the simulation result.

The atomic neutral environment causes charge-exchange collisions with the fast beam ions creating slow ions. A small percentage of the CEX ions are influenced by the space charge potential so that they are repelled back to the spacecraft surface. They are forming a hill with a big crater over the emitter around

the accelerator radius which is concentrated in the simulation domain with a radius of 1 cm. Most of them are repelled by the highly positive emitter potential and move away from the spacecraft surface. However, they can be a contamination hazard for other parts of the spacecraft with areas of highly negative potentials. The backflow current $I_B$ scales above the 3rd power of the ion current $I_i$.

The sputter contamination is more than 5 orders of magnitude larger than the charge-exchange backflow contamination to the spacecraft surface for both cases. Considering the maximum charge-exchange contamination risk, the sputter current is also more than 3 orders of magnitude larger than the CEX current lost in the whole simulation domain. However, one must calculate the maximum current tolerance for other parts of the spacecraft to answer the question if this small current, being 7 orders of magnitude below the emitter current, could still be a potential contamination risk.

In our simulation case, the CEX backflow current was concentrated in a radius of 1 cm around the emitter needle which is small compared to the accelerator diameter of 4 cm and does not harm other spacecraft parts. At an emission current of 250 μA, the maximum amount of charge-exchange current which still can be attracted by negative potentials was $2.22 \times 10^{-7}$ μA.

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