

XIPS Ion Thruster Grid Erosion Assessment for Deep Space Missions

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Abstract: JPL is currently assessing the applicability of L-3 Electron Technologies Inc.'s 25 cm Xenon Ion Propulsion System (L-3 ETI 25cm XIPS©) as part of an effort to infuse low-cost, technically mature commercial ion thruster systems into NASA deep space missions. For this assessment, we must determine the life of the XIPS 3-grid system to validate the thruster for long-life, high delta-v missions. Analysis of the XIPS 3-grid configuration with JPL's CEX3D grid erosion model shows that the third "decel" grid essentially eliminates (reduces by over an order of magnitude) the pits & grooves erosion of the downstream face of the accel grid that is commonly seen with 2-grid ion thruster grid systems. The decel protects the accel grid from the CEX ions generated in the downstream region of the beamlet that are guided by local potentials to the regions between the grid apertures. JPL's CEX3D accurately predicts the erosion patterns for the accel grid, though it appears to over-predict the pits & grooves erosion rates due mainly to uncertainties in incident energies and angles for sputtering ions and redeposition of sputtered material. Since the code should accurately simulate the erosion pattern but over-predict the erosion rates for both the 2- and 3-grid sets, this comparative analysis still clearly shows how the decel grid significantly suppresses the erosion of the downstream surface of the accel grid as observed in experimental tests. The results also show that the decel grid has a relatively small effect on barrel erosion (erosion of the aperture wall) and erosion of the upstream surface of the accel grid. Decreasing the accel grid voltage of the XIPS can reduce barrel (and total) erosion of the accel grid and should be considered for high ΔV missions.

I. Introduction

NASA/JPL is considering the use of commercial ion thruster technology for deep space missions. L-3 Electron Technologies Inc.'s 25 cm Xenon Ion Propulsion System (L-3 ETI 25cm XIPS©) is an attractive candidate due to its flight heritage, reliability, and performance. Several XIPS thrusters have thousands of hours of flight and ground test data, however, to accommodate high delta-v deep space missions we must validate the thruster for tens of thousands of hours of life. The Long Duration Test (LDT), and then later in the Extended Life Test (ELT), of the NSTAR ion thruster identified the erosion of the molybdenum accelerator ion extraction grid (or simply "accel grid) as a primary life-limiting mechanism for 2-grid ion thruster life^{1,2}. During the ELT, the accel grid apertures were eroded to as much as 25% beyond their original diameter; and as shown in Figure 1, pits were eroded entirely through the downstream accel grid face between many of the apertures near the thruster. The erosion on the downstream face is generally referred to as "pit & grooves" erosion while the erosion on the inside of aperture walls is referred to as "barrel" erosion. Both of these erosion types are important to minimize since they

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can compromise the structural integrity of the grids, increase neutral propellant loss, and increase the voltage required to prevent electron backstreaming.

The XIPS ion thruster uses a third molybdenum decelerator grid (“decel grid”), in addition to screen and accel molybdenum grids. To predict the long-term life and performance of the XIPS thruster, we must understand how the decel grid affects the erosion of the accel grid. Reference 3 discusses that the decel grid reduces ion current to the accel grid. Experimental tests by Brophy, et al.⁴ showed that the erosion rate for a 30 cm ion thruster found a greater than 100 times reduction in accel grid erosion when using a 3-grid compared to a 2-grid assembly. Two- and three dimensional models of grid erosion, CEX2D and CEX3D, were developed at JPL to help understand these erosion mechanisms^{2,11}. In previous efforts, these models were compared against LDT and ELT data for the NSTAR grid assembly and compare well with the erosion behavior but further improvements to the codes are necessary to validate the erosion rates. For example, and most importantly to this effort, CEX3D simulates the pits & grooves erosion patterns observed on the accel grids from the LDT; however, the erosion rates from reference 2 overestimate the initial wear rate by about 50%. This difference is due at least in part to the uncertainties in sputter yield as a function of incident energy and angle, determination of local incident angles, and the ignorance to redeposition of sputtered grid material. Therefore, in this effort we use the results for relative comparison of erosion rates and not for absolute erosion values.

A. Objective

In this paper we examine the erosion characteristics of the XIPS accel grid in the presence of the decel grid and discuss how these characteristics will affect thruster life. To facilitate this investigation we first compare the erosion of the XIPS 3-grid accel grid with erosion of the NSTAR 2-grid assembly and then compare the erosion of the XIPS accel with and without the decel grid. We also investigate methods for reducing overall grid wear. The results presented herein are for comparison of 2- and 3-grid systems and not intended to provide absolute erosion rates.

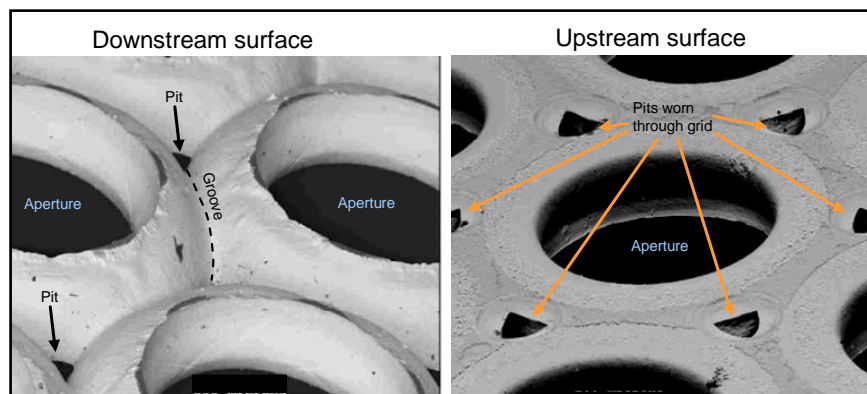


Figure 1. SEM images of the NSTAR accel grid after 30,352 hours of operation

II. Analysis and Results

In this section we compare the accel grid erosion of 2- and 3-grid geometries using JPL’s and CEX3D grid erosion models. CEX3D is used since a three-dimensional domain is necessary to accurately simulate the upstream erosion of the accel grid. All comparisons are for apertures near the thruster axis where erosion is typically greatest for both the XIPS and NSTAR thrusters due to the higher current density and intermediate neutral density near the axis^{1,5}. JPL’s ion thruster discharge model (DC-ION) was used to determine upstream ion density, neutral density, and electron temperature conditions⁶. A detailed description of how CEX3D propagates these conditions into the beamlet and computes erosion rates is given in reference 2. The axial domain for all problems is 5 cm to capture the erosion effects due to charge exchange (CEX) ions created far downstream of the grid plane. The grid geometries and thruster conditions used in the models are for beginning-of-life (BOL) and include the hot grip gap spacing observed during thruster testing⁷. Double ions are not included in the analysis, however, equivalent beam current densities are used. Throttle points used for model inputs are shown in Table 1^{1,8}.

Table 1. Typical Throttle Points for XIPS and NSTAR			
Parameter	L-3 ETI 25cm XIPS Low Power	L-3 ETI 25cm XIPS High Power	NSTAR TH15
Total Input Power (W)	2067	4215	2500
Thrust (mN)	79	165	92
Specific Impulse (s)	3400	3500	3100
Electrical Efficiency (%)	87	87	89
Mass Utilization Eff. (%)	82	84	84
Beam Voltage (V)	1215	1215	1100
Accel Grid Voltage (V)	-300	-300	-180
Decel Grid Voltage	0	0	N/A
Beam Current (A)	1.43	3.01	1.76

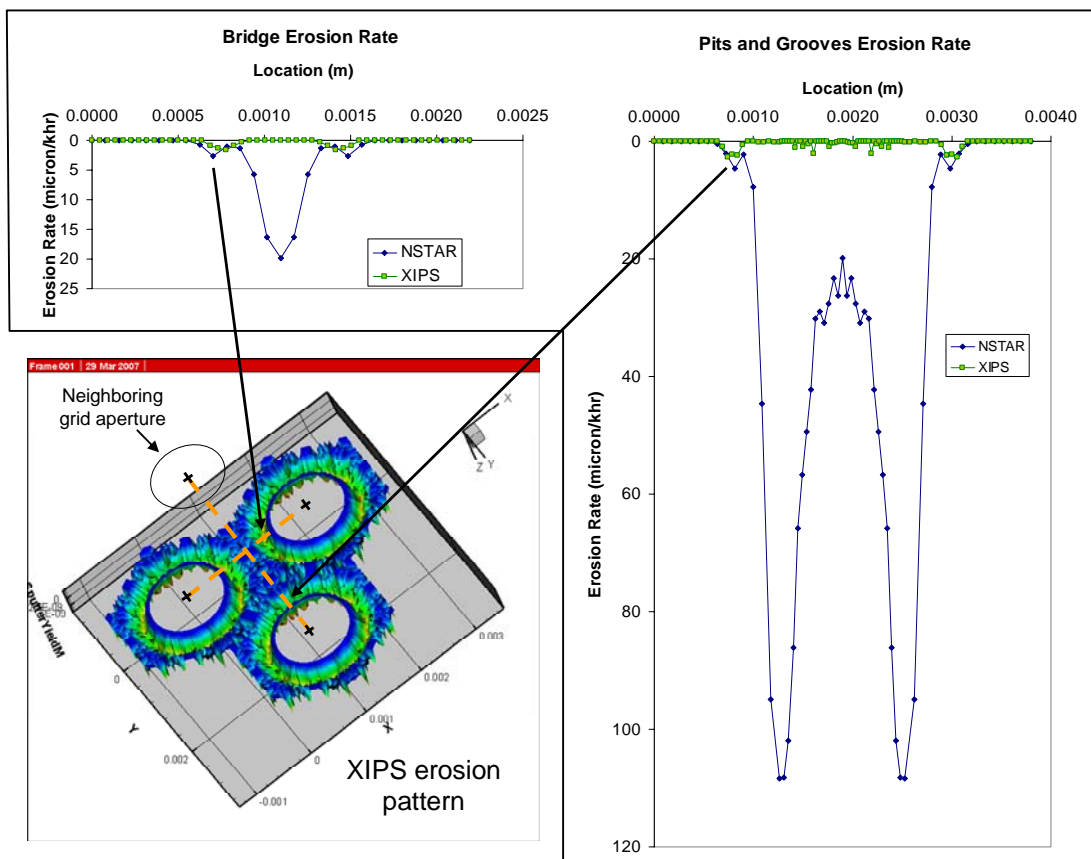


Figure 2. Comparison of erosion of the downstream face of the accel grid for NSTAR 2-grid and XIPS 3-grid geometries at TH15

A. Comparison of Accel Grid Erosion for XIPS and NSTAR Grid Assemblies

In this section we compare the BOL erosion rates of the accel grid for the XIPS 3-grid and NSTAR 2-grid systems. The grids for these thrusters have identical diameters for the screen and accel apertures, however the grid sets differ. In addition to the extra decel grid the XIPS thruster screen grid is thinner and the screen-accel grid gap is larger than those of the NSTAR thruster. The thinner screen grid tends to increase the ion transparency while the

smaller screen-accel spacing tends to decrease the ion transparency of the grids. Because the effects tend to offset each other both thrusters are comparable, although NSTAR has a slightly higher ion transparency. We compare the XIPS and NSTAR at the TH15 maximum throttle condition for NSTAR operation as indicated in Table 1. Since the diameter of the active grid area of XIPS is ~4 cm less than NSTAR, we used an upstream ion density for XIPS that is ~18% greater than that used for NSTAR in these calculations to simulate equivalent thrust levels. XIPS was run successfully at this TH15-type condition⁸.

The results from Figure 2 show that the erosion on the downstream face is much greater for the 2-grid geometry, while only a small amount of downstream erosion occurs at the periphery of the accel grid aperture for the 3-grid geometry. The corresponding downstream erosion rates for a single NSTAR and XIPS accel grid aperture are 0.826 and 0.0173 mg/khr, respectively. To understand the reason for this large difference in erosion rate we plot comparative magnitudes of erosion caused by CEX ions from the beamlet. In Figure 3 the CEX erosion rate is plotted as mg/khr/m, where “mg” is milligrams of molybdenum and “m” is meter of axial distance. These units avoid over-weighting the importance of downstream cells, since the cell sizes grow larger axially further downstream where CEX3D requires less resolution. The erosion rates in Figure 3 show that the decel grid essentially eliminates almost all of the erosion due to CEX ions created downstream of the grid plane.

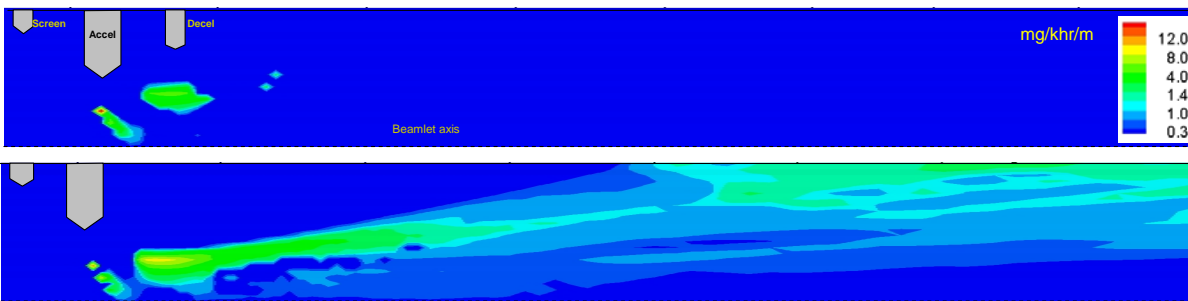


Figure 3. Erosion rate (mg/khr/m) of downstream surface of accel grid due to CEX ions created in beamlet for XIPS 3-grid (above) and NSTAR 2-grid (below). (The discharge sources are at the left-hand end of these figures. Axial domain used for CEX3D erosion calculations is ~3 times as long as shown in these images.)

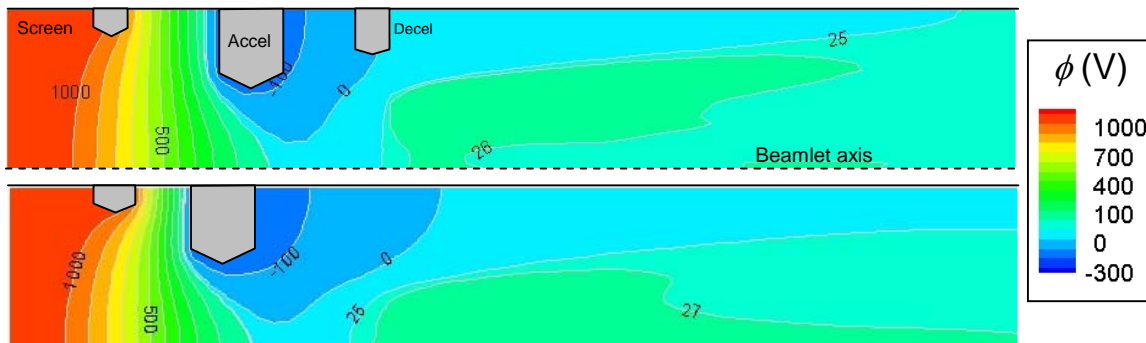


Figure 4. Potential (ϕ) profiles for XIPS 3-grid (above) and NSTAR 2-grid (below) for throttle point TH15.

The CEX ions generated in the beamlet originally have very low velocity since they are made from the relatively slow moving neutrals. The potentials in Figure 4 show that the CEX ions generated in the downstream region of the beamlet are influenced by the local electric field to move away from the beamlet axis. Therefore, for a 2-grid geometry, a large fraction of the CEX ions created downstream are guided to the “pits & grooves region” between the apertures and accelerated through a large electric field to energies (over 200 eV) that will cause relatively significant erosion on the upstream face of the accel grid as shown in Figure 1 and Figure 2. For the 3-grid geometry, most of these CEX ions are accelerated through much smaller electric fields due to the much higher potential of the decel grid (0 V), resulting in relatively low impact energies (~25 eV) incident to the decel grid. As discussed in Reference 9, the sputter yield for molybdenum is three orders of magnitude smaller at these lower energies (in comparison to energies ≥ 200 eV) and is therefore insufficient to cause noticeable erosion. This minimal erosion of the decel grid agrees with observations from XIPS long-duration tests¹⁰.

The erosion rates for the TH15 condition (as well as other conditions, discussed in the next section) are summarized in Table 2. From these values we see that the barrel erosion is similar for both geometries, though slightly lower for XIPS. The erosion of the upstream face of the accel grid is much smaller for the NSTAR grid. The lower upstream erosion for the NSTAR geometry is due to the tighter spacing of the screen and accel grids, which provides a smaller region for barrel erosion CEX ions; also the upstream ion density used for XIPS is ~18% higher. Summing these erosion values we find the total erosion rates for the NSTAR and XIPS accel grids are 0.910 and 0.131 mg/khr, respectively.

Thruster	XIPS				NSTAR	
Thruster/Throttle Level	High Power		Low Power		TH15	TH15
<i>Number of Grids</i>	<i>3-grid</i>	<i>2-grid</i>	<i>3-grid</i>	<i>2-grid</i>	<i>3-grid</i>	<i>2-grid</i>
Downstream surface	0.0463	0.912	0.0587	0.741	0.0173	0.826
Aperture wall (Barrel)	0.562	0.750	0.104	0.094	0.070	0.076
Upstream surface	0.213	0.225	0.0116	0.00914	0.0432	0.00832

B. Effect of Decel Grid on Accel Grid erosion for the XIPS 3-grid configuration

In this section, we employ results from JPL’s CEX3D code to understand how the decel grid affects accel grid erosion by comparing results for identical accel and screen grids with and without a decel grid, assuming XIPS grid geometries and spacing. Figure 5 compares the “pits & grooves” and “bridge” erosion for the XIPS 3-grid with a hypothetical XIPS 2-grid configuration (assuming the decel grid is removed) for the XIPS high power throttle point. As discussed in the previous section, these results show that the decel grid effectively shields the downstream face of the accel grid from erosion except for a small amount of erosion just around the periphery of the accel grid aperture. Referring to Table 2, the decel grid reduces the downstream accel grid erosion over an order of magnitude for both power levels. From the potential distribution downstream of both geometries for high power (Figure 6) and low power we see that the majority of the CEX ions generated downstream are guided away from the center of the beamlet by the electric field and back toward the region between the apertures.

Referring to Table 2, results for the XIPS low and high power conditions show that the barrel and upstream surface erosion rate is much less at low power. This reduced erosion for the low power condition is due in part to the better beam focusing (hence smaller beamlet diameter at the accel grid plane), in addition to lower beamlet current. Increased beamlet focusing (a.k.a. operating closer to the optimal perveance fraction) results in lower hole wall erosion since, upstream of the accel grid, only the CEX ions created near the edge of the beamlet contribute to barrel erosion, while the CEX ions created near the center of the beamlet tend to get accelerated into the beam¹¹. These results show that better focusing also reduces the upstream erosion rate.

For the high power condition, the barrel erosion for the 2-grid geometry is about 33% greater than the 3-grid geometry (0.750 and 0.562 mg/khr, respectively). This difference appears largely due to the near-axis electric field just downstream of the accel grid; for the 2-grid geometry the potential field (Figure 6) is such that a larger fraction of the downstream CEX ions are generated in a potential field that will guide them back to the accel grid hole wall. Upstream erosion of the accel grid is slightly higher for the 2-grid geometry, 0.225 mg/khr compared to 0.213 mg/khr for the 3-grid geometry. Therefore, the total of erosion rates for the accel grid for the 2- and 3-grid geometries at high power are 1.887 and 0.821 mg/khr respectively.

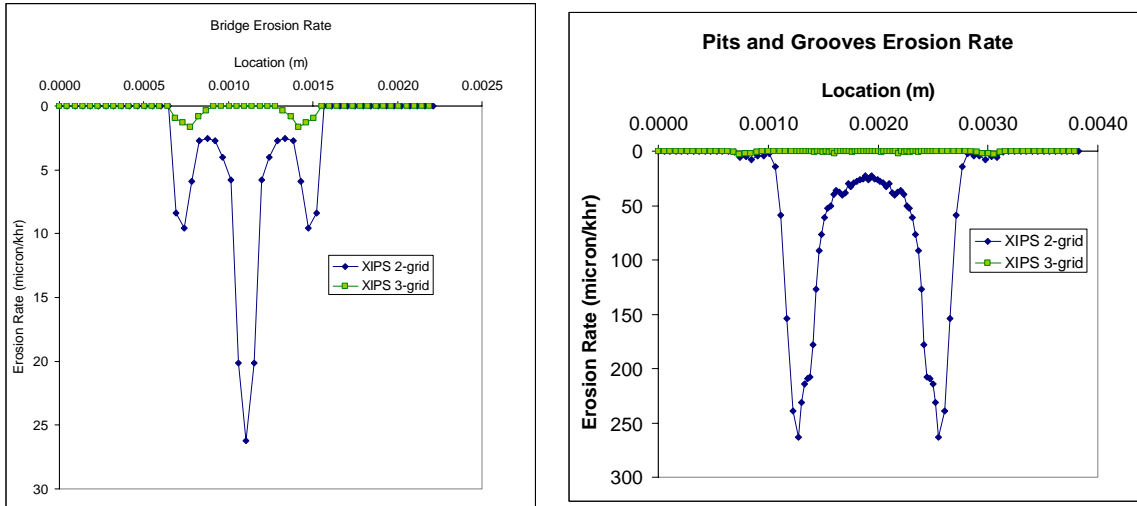


Figure 5. Comparison of downstream erosion of the accel grid for XIPS 2 and 3-grid geometry at High Power (Ordinate axis for the pits & grooves erosion is an order of magnitude greater than the Bridge Erosion plot. See Figure 2 for orientation of plots' "Location" axes)

At the low power point, we see (from Table 2) that the accel barrel erosion is ~ 11% higher and the upstream accel erosion is 27% higher for the 3-grid configuration; however, the total erosion rate for the accel grid 2-grid system is several times higher due to the much larger downstream erosion discussed above. The screen grid experiences minimal erosion for both configurations due to low incident CEX ion energies, which is confirmed by experimental observations¹.

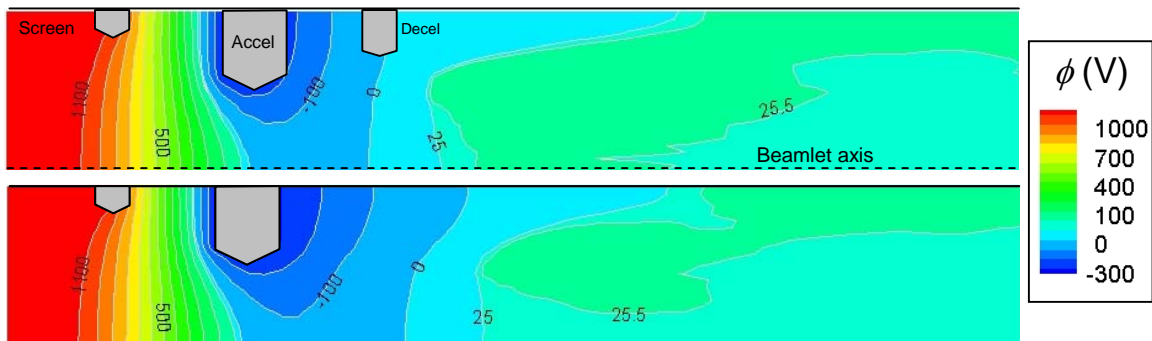


Figure 6. Potential (ϕ) profiles for XIPS 2- and 3-grid geometries at High Power throttle condition

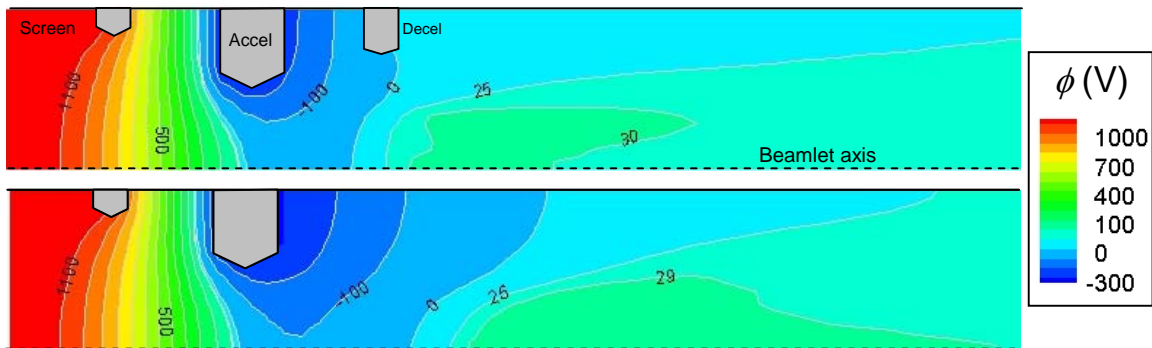


Figure 7. Potential (ϕ) profiles for XIPS 2- and 3-grid geometries at Low Power throttle condition

C. XIPS Accel Voltage Sensitivity

From the above results we see that the barrel erosion rate for the XIPS low power condition (0.104 mg/chr) is noticeably higher than the rate for XIPS at TH15 (0.070 mg/chr). Since the two conditions use similar upstream plasma conditions, it is apparent that the lower voltage of the XIPS accel grid for the low power case (-300 V compared to 180 V for TH15) is likely the primary reason for the increased erosion rates, due to increased impact energy of the CEX ions. Since the backstreaming limit for the XIPS grid system at BOL occurs at accel grid values higher than the conservative value -300 V, we can examine the change in erosion rate at higher accel voltages⁸. To do this we ran the model for accel voltages -300, -240, and -180 V. The results from this analysis, shown in Figure 8, suggest that higher accel voltages will noticeably decrease barrel erosion for the XIPS accel grid. However, for the high power case, an accel voltage of -180 V increases the upstream erosion due to direct impingement due to under focusing of the beam. From these results we see that the optimal accel voltage from an erosion standpoint is higher than the standard -300 V operating; however one must consider electron backstreaming and changes in thruster geometry due to erosion to determine the most desirable accel grid voltage for long-term mission performance.

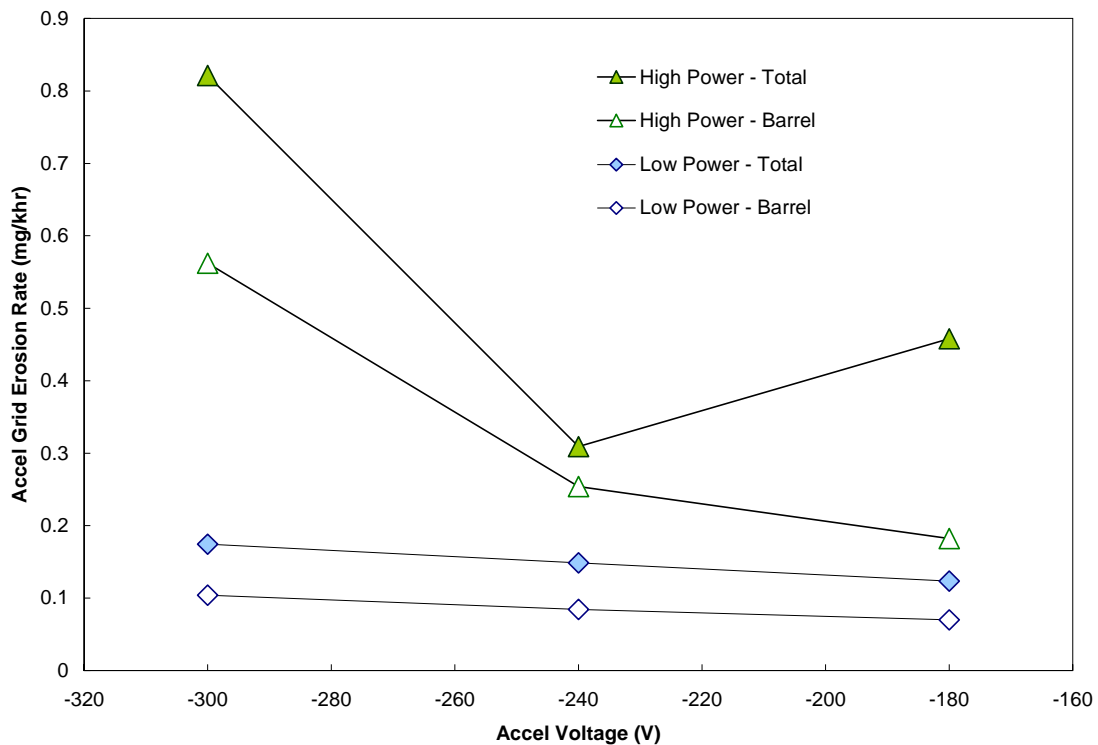


Figure 8. Barrel erosion vs. accel grid voltage for XIPS grid set (with trend lines)

III. Discussion and Conclusions

Analysis of the XIPS grids with JPL's CEX3D grid erosion model shows that, for BOL, the decel grid significantly reduces the total erosion rate of the accel by essentially eliminating the pits & grooves erosion of the downstream accel surface commonly observed for two grid systems. For all operating conditions and geometries examined herein, the decel grid reduced the downstream erosion of the accel grid by over an order of magnitude. Examining the results, it is apparent that most of the CEX ions created in the downstream region of the beamlet are accelerated away from beamlet axis and towards the pits and grooves region of the accel grid. For a 2-grid geometry these CEX ions are accelerated through a potential of at least 200 V, due to the low potential of the accel grid (~ -300 to -180 V), before impacting the upstream surface of the accel grid at energies sufficient to cause the significant pits & grooves erosion seen in many experiments. For a 3-grid geometry with the decel grid at only 0 V, the

majority of these pits & grooves ions see only a ~ 25 V potential drop, thus attaining energies that lead to sputter yields that are three orders of magnitude less than yields for the ≥ 200 V ions for the 2-grid case. Therefore, the decel grid protects the accel grid from pits & grooves erosion while sustaining minimal erosion of its own upstream surface. These observations are summarized schematically in Figure 9.

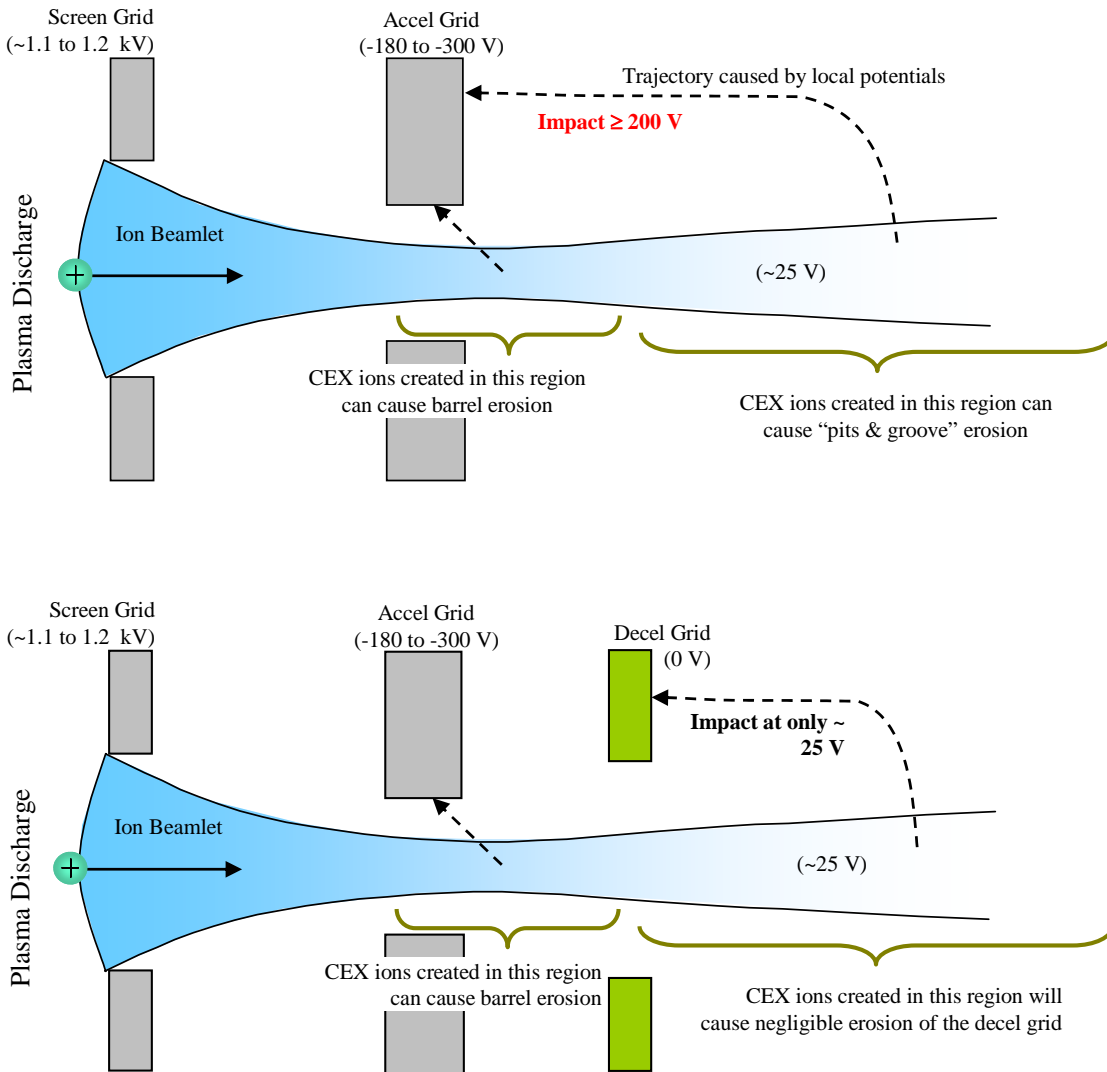


Figure 9. CEX ions created in the downstream region of the beamlet attain significant impact energies in the 2-grid configuration, leading to the pits & grooves erosion seen during NSTAR testing. In a 3-grid geometry, the decel grid essentially protects the accel grid while sustaining minimal erosion due to much smaller impact energies.

JPL's CEX3D accurately predicts the erosion patterns for the accel grid, though it appears to over-predict the pits & grooves erosion rates due mainly to uncertainties in incident energies and angles for sputtering ions and lack of knowledge of redeposition of sputtered material². Since the code should accurately simulate the erosion pattern but over-predict the erosion rates for both the 2- and 3-grid sets, this comparative analysis still clearly shows how the decel grid significantly suppresses the erosion of the downstream surface of the accel grid as observed in experimental tests^{10,11}.

Erosion rates for the aperture wall (barrel) were similar for the cases examined; the most significant change was seen when the decel grid was removed from the XIPS thruster at high power, resulting in a 33% increase in barrel

erosion for the hypothetical 2-grid XIPS geometry. As expected, decreasing the accel grid voltage of the XIPS reduces barrel erosion of the accel grid. For beginning-of-life, the results show that a accel voltage as low as -180 V will decrease erosion of the accel grid for the low power case, while a voltage between -300 and -180 V is optimal for the XIPS high power condition from an erosion standpoint.

The significantly higher erosion for the XIPS high power case is due to the fact that the beamlet is far from the optimal perveance fraction. Essentially, at low power and TH15 the beamlets are much better focused (closer to the optimal perveance fraction compare with the high power case) and a larger fraction of CEX ions are created near the beamlet axis upstream of the grid plane; from the near-axis location the CEX ions are more likely to be accelerated into the beam instead of into the grids where the cause erosion¹¹. For the high power case, the beamlet occupies more of the aperture region away from the beamlet axis; CEX ions created on the periphery of these large beamlets are likely to cause erosion of the accel grid.

In future analyses we will use additional experiments and computational modeling to determine the optimal accel grid voltage for long term thruster life and performance to meet NASA mission needs. These efforts will include consideration of the electron backstreaming, double ion effects, detailed erosion estimates for all grid surfaces, and the influence of the temporal morphology of the grids on long-term erosion and electron backstreaming limits. Another possible improvement to the codes is the inclusion of redeposition of the sputtered grid material

Acknowledgments

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