Assessment of Grid Impingement for Electrospray Thruster Lifetime

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Colloid Micro Thrusters (CMT) for use on the upcoming Laser Interferometer Space Antenna (LISA) mission need to ensure low grid impingement for long operational life. Updated lifetime predictions are developed based on experiments and computational models of a single emitter of the CMT. Measured mass flux and current density profiles of a 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-Im) electrospray plume are shown to not share the same distribution. Most notably the mass flux exhibits more rapid decay with polar angle than current density. A simple model accelerates the measured mass flux distribution, which results in negligible grid impingement, suggesting that steady, on-axis emission is unlikely to provide life-limiting overspray conditions for the LISA CMT. Transient behavior of the plume is also considered, with modeling showing wide particle trajectories resulting from negative velocity gradients in the plume. The EMI-Im cone-jet deviates significantly off-axis for emitter-extractor voltages a couple of hundred volts above the nominal 1.60 kV for CMT, which lead to much-increased grid impingement. Off-axis emission is much less sensitive to flow rate suggesting thrust setpoints should generally be commanded by changing flow rate rather than voltage. Transient instabilities manifesting from accumulated propellant at the emitter tip were further shown to impinge heavily on the grids. Therefore, operating procedures that lead to accumulated propellant on the emitter should be avoided for longer electrospray lifetime.

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Nomenclature

\( u \) = Pseudo-particle initial velocity \((u_\rho, u_z)\)
\( v \) = Pseudo-particle final velocity \((v_\rho, v_z)\)
\( \dot{m} \) = Mass flux
\( \Gamma (\theta) \) = Measured plume mass flux
\( \Gamma_{\text{acc}} (\theta) \) = Accelerated measured plume mass flux
\( \rho \) = In-plane radial direction
\( \rho_0 \) = Pseudo-particle beginning displacement from emitter axis
\( \theta \) = Plume polar angle
\( a \) = Pseudo-particle acceleration
\( A \) = Internal cross-sectional area of the capillary
\( b \) = Super-Gaussian width
\( d \) = Emitter separation distance
\( d_{ea} \) = Extractor-accelerator separation distance
\( d_{ee} \) = Emitter-extractor separation distance
\( f (\theta) \) = Super-Gaussian profile
\( G \) = Super-Gaussian normalization factor
\( j (\theta) \) = Measured plume current density
\( j_{\text{acc}} (\theta) \) = Accelerated measured plume current density
\( \text{LOS}_A \) = Line of sight angle to accelerator grid
\( \text{LOS}_E \) = Line of sight angle to extractor grid
\( m (\theta) \) = Pseudo-particle mass
\( n \) = Super-Gaussian order
\( Q \) = Flow rate
\( q (\theta) \) = Pseudo-particle charge
\( r_0 \) = Pseudo-particle beginning displacement from emitter
\( R_E \) = Extractor aperture radius
\( s_\rho \) = In-plane radial displacement
\( s_z \) = Axial displacement
\( T \) = Total thrust
\( V_{0^\circ} \) = Emitter-extractor potential difference to maintain cone angle displacement \( \leq 1^\circ \)
\( V_{ea} \) = Extractor-accelerator potential difference
\( V_{ee} \) = Emitter-extractor potential difference
\( z \) = Axial direction
\( z_d \) = Downstream distance from emitter tip
I. Introduction

Electrospray thrusters were first operated in space in 2015 as the technology demonstration of the Colloid Micro-Newton Thrusters (CMNTs), developed by Busek Co., Inc. and NASA Jet Propulsion Laboratory (JPL) for the European Space Agency (ESA) Laser Interferometer Space Antenna (LISA) Pathfinder mission. The CMNTs demonstrated key mission capabilities such as micronewton thrust precision and low thrust-noise. Seven of the eight CMNTs operated in space for over 2,400 hours and a ground-based test ended after 3,400 hours without failure. The LISA mission requires nearly 40,000 hours of operational lifetime, and 60,000 hours for the extended mission, expected to launch in the 2030’s. Therefore, understanding life-limiting mechanisms in electrospray thrusters is necessary to improve their viability for LISA and other future missions. The LISA Colloid Microthruster Technology (CMT) development plan, described by Ziemer et al., is using lessons learned, trade studies, and physics-based modeling to predict the performance and lifetime of the LISA CMT and guide system design. As part of the CMT development plan, researchers from the University of California, Los Angeles (UCLA) Plasma & Space Propulsion Laboratory (PSPL) have undertaken a multi-faceted campaign to investigate CMT performance and life.

The first iteration of the UCLA Electrospray Life Model (ELM), presented by Thuppul, Wright, and Wirz, was developed as a first step to probing lifetime of an electrospray thruster under conditions commensurate with the Space Technology 7 Disturbance Reduction System (ST7-DRS). A simplified schematic of a single emitter from the ST7-DRS thruster head is shown in Fig. 1. For the stated requirement of 60,000 hours of life for the extended mission, it was shown that impingement of propellant (ionic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-Im)) to the accelerator grid from the edges of the plume (“overspray”) was the primary life-limiting mechanism. Using literature-based scaling relations and empirical fits to data from complete (nine emitter) thruster heads thruster lifetime was estimated given the nominal geometric conditions for the ST7-DRS thruster. Improvements were suggested following modest geometric changes to the thruster, and careful tracking of tolerance stack-ups.

The analytical ELM provided useful insight into how propellant “overspray” could occur and be potentially mitigated, but many assumptions were required to infer critical aspects of the plume, most notably mass and charge distribution within the plume. To develop the next generation of ELM, data and multi-scale modeling were required to improve understanding of electrospray plume dynamics and better-predict life-limiting mechanisms. The ELM is developed synergistically with experimental and computational data (exemplified in Fig. 2): the ELM informs what parameters need to be measured and/or calculated, and results from experiments and models provide realistic numbers for lifetime analysis and phenomenology.

The state of the ELM (with its associated experiments and models) at UCLA PSPL and its implications for CMT lifetime analysis are reviewed henceforth.

![Figure 1. Electrospray emitter and grid geometry with line of sight plumes, LOS_E and LOS_A, along with intercepted mass flux and current.](image-url)
II. Electrospray Life Model - Single Emitter

Previous models for estimation of thruster lifetime\(^7\) made use of current density measurements of the plume generated by a complete thruster head. The complete thruster used in the ST7-DRS consisted of nine capillary emitters in a 3×3 array.\(^{10}\) The plume from an array of multiple emitters is the superposition of individual plumes that are spatially offset, assuming minimal Coulombic interaction downstream. Mechanisms for thruster failure, such as overspray, typically arise within single emitters. Since the superposition of multiple plumes does not necessarily produce a unique plume, any information regarding plume dynamics coming from a single emitter can be lost.

A. Plume Superposition

A plume consistent with the observations of Thuppul \textit{et al.}\(^{11}\) is shown in Fig. 3, superposed with eight more identical plumes, each emanating from emitters separated a distance \(d\) from each other in a 3×3 array. The plume that would be measured in a plane at various distances \((z_d)\) from the emission plane is shown as a function of linear and angular distance from the central emitter axis; plumes are normalized by their peak value. The profile across the center of the plume is also shown. Though the single-emitter input plume is not Gaussian, the 3×3 profiles go from multi-peaked near the emission region \((z_d \lesssim 4d)\), to a near-Gaussian profile \((z_d \approx 4d)\), and then further downstream \((z_d \gtrsim 10d)\) the total plume approaches the distribution of the single-emitter plume. Fig. 4 further shows how a cross-section of the plume develops to eventually match that of the single emitter when measured far enough downstream \((z_d \gtrsim 10d)\).

Multi-emitter plumes must be interpreted with care since they are not necessarily representative of the emission profile from the individual emitters. When the individual emitters exhibit different emission profiles \(\text{(e.g. by design, through malfunction, or simply from tolerance stack-up)}\), extracting individual emitter information becomes even more challenging, adding further uncertainty to measurements and performance.

If measurements are to be taken of a multi-emitter plume, the data will only be representative if it is taken far enough downstream that geometric information about the array dimensions is blurred out. The most sensitive measurements may, however, need to be taken close to the emitter. Given the apparent complexities imposed by multiple emitters, to proceed with meaningful calculations and measurements for lifetime analysis, the UCLA Plasma & Space Propulsion Laboratory (PSPL) consider single emitters only. With calculations and measurements of single-emitter behavior, summed plumes can be readily generated, while retaining information about life-limiting behavior at the single-emitter level.

B. Experimental Systems

Two experimental systems have been commissioned to provide important data on electrospray performance and lifetime estimation.

1. \textit{The Atmospheric Pressure Electrospray eXperiment (APEX)}

APEX is a simple apparatus to perform canonical electrospray experiments and aid in diagnostic development. The system has been described previously by Wright, Thuppul, and Wirz,\(^8\) and by Wirz \textit{et al.}\(^5\).
Figure 3. Superposition of electrospray plumes from a $3 \times 3$ array of emitters, shown at various distances downstream. Plume development with linear (a) and angular (b) distance is shown, as well as a cross-section of the angular distribution (c). Plumes are normalized by their peak value.

Figure 4. Cross-section of the angular distribution of an idealized single-emitter electrospray plume, and the superposed electrospray plume generated from a $3 \times 3$ array of emitters. Plumes are normalized by their peak value. Far downstream the superposed distribution approaches that of the single-emitter distribution.
APEX consists of a capillary emitter, an extractor that can be moved relative to the emitter, high speed current measurements on the extractor and emitter, as well as high speed microscopy capability. High speed microscopy of the various modes of an ethanol electrospray emission, which informs lifetime considerations, were presented by Wright, Thuppul, and Wirz. Uchizono et al.\textsuperscript{12} used APEX to show how current measurements can be used to diagnose pulsation modes, which could lead to overspray\textsuperscript{13} and life-limiting events.

2. The Highly Optimizable Apparatus for Groundbreaking Investigations of Electrosprays (HOAGIE)

HOAGIE is a vacuum-based system ($\lesssim 10^{-6}$ torr), with an ever-growing suite of diagnostics to quantify performance and provide physical understanding of electrospray plumes. A schematic of HOAGIE diagnostics is shown in Fig. 5. HOAGIE is designed to be adaptable and expandable to incorporate off-the-shelf, and in-house-developed, diagnostics. While it is currently arranged for ST7-DRS geometry conditions, there is minimal restriction on the particular electrospray that can be measured.

![Schematic of the HOAGIE setup](image)

Figure 5. Schematic of the HOAGIE setup in its present form. The system is a single emitter and extractor setup, with electrospray being achieved by applying an appropriate voltage between the extractor and emitter. Key diagnostics are current measurement, high speed microscopy with a Long Distance Microscope (LDM), and current probe + QCM mounted on an armature able to traverse the plume.

A pressure-over-fluid (POF) system with precision mass flow controllers feeds EMI-Im propellant to a capillary mounted on a stage with 2 perpendicular rotation axes inside a vacuum chamber. The capillary is typically mounted 90$^\circ$ to an extractor grid (having 3 translational degrees of freedom), but can be oriented at arbitrary angles to measure the consequences of misalignment to the plume. Stereoscopic optics and microscopes allow 3-dimensional viewing to aid with alignment, as well as \textit{in-situ} microscopy during electrospray emission. A long distance microscope and in-house optics allow viewing of the cone-jet from outside the HOAGIE vacuum chamber, with high speed video available. Electrospray is achieved by applying a voltage between the emitter and extractor. An armature is mounted on an $x$-$y$ translation stage, with an additional rotation axis, to sweep a Quartz Crystal Microbalance (QCM) and current probe through an electrospray plume for direct mapping of current density and mass flux. Multiple high-speed current monitors are available for measuring grid and emitter currents. An accelerator grid is not currently present, but can be simply added.

HOAGIE has been designed to simplify the electrospray system where possible to investigate fundamental physical behavior, that can be propagated to the system level, and inform lifetime. Recent data from the HOAGIE facility are presented by Thuppul et al.;\textsuperscript{11} Uchizono et al.;\textsuperscript{12} Wirz et al.;\textsuperscript{5} and Wright et al.\textsuperscript{14}
Data from Thuppul et al.\textsuperscript{11} and Uchizono et al.\textsuperscript{12} are utilized in the present study to probe the relative importance of potential life-limiting mechanisms.

C. Modeling Framework

The UCLA PSPL has discretized an electrospray into distinct regions for computational modeling, as shown in Figure 6. The regions are distinguished as follows:

1. Extraction Region: The electrostatic force overcomes the fluid surface tension to form a cone-jet and generate droplets. The simulation for the region utilizes computational fluid dynamics (CFD) analysis under incompressible and axisymmetric assumptions.

2. Transition Region: Coulombic fission and ion evaporation cause off-axis behavior of droplets.

3. Interaction Region: Droplet breakup and inter-particle Coulombic interactions cause the plume to expand.

4. Plume Region: Coulombic interactions no longer dominate the particle dynamics.

Figure 6. Overview of the UCLA PSPL electrospray modeling suite, which aims to identify the underlying physics of unstable modes that lead to reduced lifetime.

1. Extraction and Transition

An Electrohydrodynamic (EHD) OpenFOAM solver (PSPL-EHD) has been developed in-house, based on the electrowetting model to understand the physics of a cone-jet and droplet formation in the Extraction and Transition regions of an electrospray.\textsuperscript{15} The code requires no simplification of the charge conservation laws and includes improvements to handle the uniquely challenging properties of highly-conductive propellants.\textsuperscript{16} Gauss's law and the charge conservation equation are solved along with the Navier-Stokes equation for flow-field and charge distribution. The Extraction and Transition Models are not limited to steady-state behavior, so can provide useful information on the instabilities that can lead to off-axis emission and subsequently reduced lifetime.
3. Interaction

The Interaction Model is a discrete element particle-pushing model that has also been developed in-house.\textsuperscript{13} The Interaction Model simulates electrospray droplet dynamics immediately downstream of the Transition Region, through expansion into the Plume Region. Results from the Transition Region regarding droplet sizes and velocities can provide initial conditions to the Interaction Model, and be propagated downstream. The key simulation result offers insight into how velocity differences between droplets provoke “traffic jams” with resulting large-magnitude Coulombic interactions that facilitate plume expansion. The model successfully captures the propensity of lighter, high-specific-charge droplets to reach wide plume angles and heavier, low-specific-charge droplets to remain at narrower plume angles.\textsuperscript{17, 18}

Thruster lifetime has a substantial dependance on grid impingement, resulting from the pushing of droplets and ions to wide half-angles. Understanding the source of plume expansion in the Interaction Model\textsuperscript{13} allows fluid properties to be explored with the Extraction Model,\textsuperscript{16} in order to reduce “overspray” through system design.

D. System Considerations

The large Coulombic-interactions resulting from particle velocity disparities have been shown to occur within a relatively short distance downstream from the emitter tip.\textsuperscript{8, 13} It is therefore expected that Coulombic interactions are complete well before the extractor plane is reached. Beyond the point of last Coulombic scattering (\textit{i.e.} the point beyond which Coulombic interactions subside), particles are free to be directed by external electric fields only. Measurements taken within the plume and beyond the extractor (in the absence of substantial electric fields) are therefore direct representations of the plume at the point of last scattering. There is confidence that the plume-sweep measurements from within HOAGIE that are taken beyond the extractor, and without an accelerator, are a faithful representation of the plume, which can be theoretically accelerated and the plume parameters propagated into a lifetime estimate.

At the system level, UCLA PSPL seeks to gain a comprehensive understanding of the entire electrospray process, where experiments and interpretation complement results from the Extraction and Interaction Models. With comprehensive understanding of the electrospray process, lifetime estimation can be achieved by mapping appropriate modes. The first mode that has been identified for closer analysis is grid impingement, with end-of-life being defined when propellant absorption into a grid has reached a threshold amount of its open volume.\textsuperscript{7}

III. Calculating Steady-State Grid Impingement

With new data available on plume constituents and understanding via modeling, the ELM can propagate a measured plume profile downstream as if an accelerator grid were present, and improved estimates of grid impingement can be made under steady emission conditions. It is assumed that downstream from the extractor there is minimal change to the particle species since passing through the extractor grid. A summary of relevant dimensions for the calculation is shown in Fig. 7.

In the region between the extractor and accelerator, the accelerating field is well-approximated by assuming parallel plates, separated by a distance, $d_{ea}$, and held at a potential difference, $V_{ea}$, which provides an acceleration, $a$, to the particle of

$$a = \frac{q(\theta)}{m(\theta)} \frac{V_{ea}}{d_{ea}} = \frac{j(\theta)}{\Gamma(\theta)} \frac{V_{ea}}{d_{ea}},$$

(1)

where $q(\theta)$ and $m(\theta)$ are the charge and mass respectively of a test particle entering the extractor-to-accelerator region at an angle $\theta$ from the centerline. $j(\theta)$ and $\Gamma(\theta)$ are current density and mass flux per steradian as measured in the HOAGIE facility. The extractor aperture radius is small enough that the field generated between the extractor and emitter minimally-penetrates the region beyond the extractor, but future efforts should make use of the fully distorted field.

Even with relevant plume data, assumptions still need to be made to propagate the plume downstream. The velocity distribution of the plume is not currently known, and is highlighted as a requirement for future measurements. Presently, the velocity distribution is assumed through energy considerations. The speed $|\vec{u}|$
at any given angle is given by

\[ |u| = \frac{Q}{A} + \sqrt{2V_{ee} \frac{j(\theta)}{\Gamma(\theta)}}, \]

where \( Q \) is the input flow rate to the emitter, \( A \) is the capillary area, and \( V_{ee} \) is the emitter-extractor potential difference. Since the mass flux and current density profiles are taken as projections of the plume from the extractor plane, and there is no field assumed beyond the extractor in HOAGIE, the direction of a test particle is given by the measurement angle itself.

For a mass flux element, \( \delta m(\theta) \), beginning at the extractor plane, the pseudo-particle is accelerated in the \( z \)-direction until it reaches the accelerator plane, and the velocity, \( (v_s, v_z) \), can be simply calculated under constant vertical acceleration. The thrust provided by the mass flux element, \( \delta T \), is

\[ \delta T = \delta m(\theta) \delta v_z(\theta), \]

and the total thrust, \( T \), is the integral of the thrust elements from the central axis (\( \theta = 0 \)) to the line of sight angle of the accelerator (\( LOS_A \)). By means of an example, calculated particle tracks for spray conditions given by plumes measured within HOAGIE at 1.02 nl s\(^{-1}\) are shown in Fig. 8. Mass flux and current density data from the HOAGIE facility result from the convolution of the plume distribution and the measurement probe, which results in a rounded top-hat-like function.\(^{11}\) The data as presented here are conveniently fitted with a Super-Gaussian profile, \( f(\theta) \), (Eq. 4),\(^{19}\)

\[ f(\theta) = G \cdot \exp \left( -\left( \frac{\theta}{b} \right)^{2n} \right), \]

where \( G \) is a normalization factor, \( b \) is the width of the Super-Gaussian, and \( n \) is the order of the Super-Gaussian, denoting how rapidly the function decays. There is no implication that the underlying distribution has an explicitly Super-Gaussian form, beyond its flattened peak and sharper-than-Gaussian decay at high half-angles.

The accelerated mass flux (\( \Gamma_{acc}(\theta) \)) and current density (\( j_{acc}(\theta) \)) given mass flux and current density input distributions (\( \Gamma(\theta) \) and \( j(\theta) \)) are shown in Fig. 9, again for plumes measured in the HOAGIE facility at 1.02 nl s\(^{-1}\). The accelerator successfully increases the thrust and tightens the plume such that impingement of propellant on the accelerator grid is substantially reduced. Figure 10 shows in polar form the mass flux at the accelerator grid, to exemplify how mass is directed closer to the emitter-axis by the accelerator.
Figure 8. Calculated average particle tracks for nominal steady spray conditions.

Figure 9. Input (blue) and accelerated (red) mass flux (a) and current density (b) for Super-Gaussian fits to data generated within HOAGIE at \( Q = 1.02 \text{ nl s}^{-1} \).
A. Mass Flux Beyond Line of Sight Angle

A key result from experimental testing in HOAGIE, and its subsequent analysis, is that the mass flux and current density of the plume do not share the same distribution, which has implications for how the plume would be accelerated as the charge-to-mass ratio is what matters (see Eq. 1). Furthermore, while the current density is almost Gaussian in nature, the mass flux is most certainly not, with a flat-top distribution evident and a much sharper drop-off with half-angle (θ) than that of a Gaussian over many thrust and voltage setpoints. Sharply decaying mass flux with half-angle is beneficial for lifetime, because the tails of the distribution contain much less mass than would be expected for a Gaussian plume of similar width, and hence the accelerator and extractor grid impingement rates are much lower. Figure 11 shows a Gaussian mass flux (n = 1), and Super-Gaussian mass flux (n = 3.82), each having the same width (b = 27.3°) and total flux; the Super-Gaussian is a fit to data.

![Figure 11. Super-Gaussian (blue, n = 3.82) and Gaussian (red, n = 1) input (a) and accelerated (b) mass fluxes having the same width (b = 27.3°) and total mass flux. The insets show the much larger propagation of the Gaussian profile beyond the extractor and accelerator aperture line of sight angles (LOS<sub>E</sub> and LOS<sub>A</sub>).](image)

The thrust from the accelerated plume in both cases was calculated to be 2.9 µN, but the larger tail of the Gaussian plume beyond the accelerator aperture (highlighted in purple) and extractor aperture (highlighted...
in yellow) results in a much larger grid-impingement than for the Super-Gaussian-fit plume and hence substantially reduced lifetime. The accelerator is successful in reducing the amount of propellant impinging on the grids, but the Gaussian plume still shows substantially more flux beyond $LOS_A$. Indeed, when the mass flux is integrated beyond $LOS_A$ to calculate the propellant accumulation rate and estimated lifetime (as in Thuppul et al.), the Gaussian plume case is estimated to reach grid saturation after $\sim 15,000$ hours with the Super-Gaussian plume reporting $\sim 10^{189}$ hours of life (or more realistically well beyond the required lifetime of the thruster).

Even at higher flow rates where plumes expand to larger half-angles, the probability of grid-impingement is very small over a large range of operating conditions, due to the rapid decay of mass flux with polar angle (as measured in the HOAGIE facility) and tightening of the plume with acceleration. Therefore, lifetime estimates using measured mass flux profiles show that steady-state on-axis emission does not provide enough propellant to saturate the grids through overspray to limit lifetime.

Phenomenology from the experimental results and analysis of Wright, Thuppul, and Wirz with further modeling-based analysis from Davis, Collins, and Wirz suggests that overspray conditions (i.e. wide particle trajectories) will occur when negative velocity gradients are produced at emission. The stability of EMI-Im emission shown by Uchizono et al. indicates that during steady emission such velocity gradients, arising from break-up instabilities, are suppressed, and as such steady emission is not expected to produce overspray.

IV. Off-Nominal Modes

The Space Technology 7 Disturbance Reduction System (ST7-DRS) showed evidence of thruster failure due to propellant bridging between the grids, which would be a result of plume overspray. However, it was shown in the previous section that overspray is unlikely during steady, nominal operation of the thruster. Grid-impingement must occur during planned, or unplanned, deviations from nominal steady cone-jet emission and such less-stable modes should be considered as sources of propellant overspray; the origins of less-stable modes are discussed herein.

A. Time-Dependent Emission Modes

Prior data from the APEX apparatus (and many historical studies) have shown that for low conductivity fluids there are a number of electrospray modes achievable over a range of voltages and flow rates. From the perspective of lifetime, steady on-axis cone-jet mode does not appear to provide sufficient flux to the grids to limit lifetime, but other, more time-dependent, emission modes (e.g. pulsating, whipping, multi-jet) can easily provide substantial off-axis emission. Whipping and multi-jet modes are explicitly off-axis phenomena, whereas pulsations can increase velocity disparities in the plume, leading to wider particle trajectories (as postulated by Wright, Thuppul, and Wirz, and Davis, Collins, and Wirz).

Uchizono et al. have shown, using the HOAGIE facility, that:

“No pulsating, whipping, or multi-jet instabilities were observed in the steady-state stability experiment test.”

Temporally-steady emission modes for EMI-Im are found over a large range of voltages and flow rates (a substantially larger range than that found for ethanol). While the experiments may not be capturing pulsations at frequencies $\gtrsim$ MHz, there is some confidence that given the high conductivity and viscosity of EMI-Im, unstable electrospray emission modes that would lead to greater off-axis emission are somewhat suppressed, and so are of reduced concern for lifetime estimation.

B. Axial Displacement

Over the range of voltages and flow rates tested by Uchizono et al., an “axial displacement” was observed, in that the cone-jet itself would deviate from the emitter-axis as a function of voltage and flow rate. Fig. 12 shows the cone-jet angle displacement observed by high-speed camera, and also captured by the QCM plume-sweep measurements. The measured displacement angle as a function of voltage and flow rate is also shown; the green area of the surface plot highlights a cone angle of $< 1^\circ$. The angle of cone-jet displacement cannot be explicitly known from the measurements of Fig. 12, rather each observed angle is a projection of the displaced cone-jet/plume into either the image plane of the camera, or the sweep plane of
the QCM. It is suspected that the displaced cone-jet results from an asymmetric concentration of electric field due to very slight misalignment of the emitter and extractor. The cone-jet and plume should remain pointing in the direction of largest field gradient, and so the azimuthal deviation angle would be consistent across different voltages and flow rates. Further analysis is required to understand the origin of the polar angle displacement, which can be measured with stereoscopic optics (which are available within HOAGIE).

Figure 12. Angular displacement of the cone angle as a function of flow rate and voltage: (a) measured in the HOAGIE facility by Uchizono et al.\textsuperscript{12} with a high speed camera; (b) measured by Thuppul et al.\textsuperscript{11} with a QCM. The green area of the axial displacement map (c) highlights a cone angle of $< 1^{\circ}$

It is clear from Fig. 12 that on-axis emission (0$^{\circ}$ cone angle) is achievable over a wide range of flow rates, and a smaller range of voltages ($V_{0}^{\circ} \sim 1.60 \pm 0.03$ kV). Once the voltage moves outside of the stable range, the cone angle drifts quickly, which would lead to increased mass flux to the extractor and accelerator grids (as observed by Thuppul et al.\textsuperscript{11}), reducing thruster lifetime.

As noted by Wright, Thuppul, and Wirz,\textsuperscript{8} operation of the thruster can drift away from stability-islands and into less lifetime-favorable regimes. While temporally-unstable emission appears suppressed with EMI-Im, Fig. 12 shows that small changes in voltage can lead to off-axis emission, and potentially reduced lifetime. The axial displacement-map of Fig. 12 suggests that changing the thrust by varying flow rate, rather than voltage, is appropriate as the cone angle is much less susceptible to angular-displacement when changing flow rate. Thrust setpoint changes in flight are typically achieved by commanding changes to flow rate, rather than voltage, so the likelihood of cone-jet-angle drift is reduced.

C. Setpoint Changes

Commanded thrust setpoint changes introduce off-nominal emission that could lead to lifetime reduction. Two timescales for setpoint-change emission-drift are reported.

First, Demmons \textit{et al.}\textsuperscript{10} and Ziemen \textit{et al.}\textsuperscript{1} both show system-commanded thrust setpoint changes that over- or under-shoot the commanded value for 10's of seconds. Thrust calculations are shown in Fig. 13. During commanded-thrust overshoots, or undershoots, emission is off-nominal and could move outside of the stable region of Fig. 12. Since thrust is commanded by flow rate, and the plume angle is less-susceptible to angular drift with flow rate, as well as EMI-Im not being particularly susceptible to time-variant emission modes, it is not expected that the over-/under-shoots are particularly detrimental to thruster lifetime.

Second, Uchizono \textit{et al.}\textsuperscript{12} have shown that during nominal changes to flow rate, cone-jet volume can overshoot on the 100's $\mu$s timescale. Figure 14 shows the cone-jet as the flow rate is commanded from 0 pl $s^{-1}$ to 400 pl $s^{-1}$, and from 400 pl $s^{-1}$ to 0 pl $s^{-1}$, both at 1.6 kV, with the tip of the cone-jet plotted below.

The cone-jet is observed to overshoot in the start-up case, with a small excess volume to be shed from the cone in order to reach steady state. From the perspective of lifetime, a small start-up transient overspray may be induced by the overshoot, and future efforts will aim to quantify the effect of over-volume. Conceptually, the cone-jet overshoot on start-up would lead to velocity-disparities in the plume, and hence widened particle
Figure 13. Over- and under-shoot thrust from changing setpoints, taken from (a) Demmons et al.\textsuperscript{10} and (b) Ziemer et al.\textsuperscript{1}

Figure 14. High speed video sequence of cone-jet start-up (a) and shutdown (b) by commanding flow rate between 0 and 400 pl s\textsuperscript{-1}. The lower plots track the vertical displacement of the jet tip relative to the starting position.
trajectories as the instability clears. Flow rate commanded shutdown, however, appears steady, with no temporal cone instabilities apparent. The end of the plume (i.e. the last particles emitted) could, however, provide a velocity disparity that pushes a few particles out wide. “Instability” of the plume should be considered in future studies, alongside cone-jet instabilities.

D. Off-Nominal Setpoint Changes

The apparent temporal stability of the cone-jet afforded by EMI-Im, and the observed “axial stability” with flow rate suggests that the ST7-DRS geometry would have very long life. Phenomenologically, according to the analyses of Wright, Thuppul, and Wirz, and Davis, Collins, and Wirz, any changes in thrust setpoint could lead to negative velocity gradients, and hence transient wider plumes and grid-impingement - the extent to which such transient oversprays contribute to lifetime will be considered in future studies. For now, as long as setpoint changes are kept to a minimum, and changes to operation are commanded by flow rate, substantially longer lifetimes than 60,000 hours are expected.

Figure 15. High speed video sequence of a transient whipping mode measured in the HOAGIE facility, induced by switch-on of voltage with constant flow rate.

Uchizono et al. have shown some of the consequences of off-nominal setpoint changes, namely that applying thrust by switching on voltage after flow rate, instead of vice-versa, can lead to whipping, multi-jet, and rapidly-oscillating modes. A transient whipping mode resulting from voltage switch-on is shown in Fig. 15. All modes of spraying imposed by voltage switch-on enhance high-angle emission of droplets, and are expected to contribute substantial reductions to emitter-life. By applying voltage after flow rate, propellant is able to accumulate at the emitter tip, which is then unconstrained by hydraulic resistance once the voltage is applied, leading to very unstable emission.

The off-nominal shutdown during the LISA Pathfinder mission, described by Ziemer et al., suggests a similar situation arising from propellant build-up at the emitter tip:

In the abbreviated thruster shutdown procedure, they were not heated to 40°C to electrospray residual propellant out of the emitters and the electrode voltages remained applied for the SKM over a few days. Current flickering on and off at 0.05-0.25 µA level was observed, typically only from thruster 4, during these days as propellant was drawn out with voltage applied and electrosprayed. It seems likely that this flickering electrospray during the SKM contributed to the development of the propellant bridge, as this current could be sprayed between the emitter and extractor. This thruster also demonstrated more current flickering with the valve closed during TVAC testing before integration onto the spacecraft. It sprayed more charge in this flickering mode than any other of the thrusters.

Even though the thruster was held at constant voltage and flow rate nominally shut-off, the lack of propellant suck-back would have left a finite volume of propellant at the emitter tip. If the propellant at the tip slowly grew due to a very small flow rate, having the voltage continually on would eventually lead to emission similar to that observed by Uchizono et al. for a voltage switch-on event, leading to the “current flickering” behavior observed in-flight. Furthermore, said flickering behavior would spray unstably, demonstrating the same forcing of propellant out to wide half-angles, and saturating emitter and extractor grids.

V. Conclusion

The present study represents a continuation of electrospray thruster lifetime analysis considered by the UCLA Plasma & Space Propulsion Laboratory. Prior lifetime analysis made useful predictions, but lacked information to reduce uncertainties. Experiments and models were commissioned to provide information required for better lifetime analysis. Single emitters are considered in models and experiments, lest the
superposition of multiple emitters in a typical thruster obfuscate measurements. Analysis focused on propellant “overspray” to the accelerator and extractor grids, which is considered to be the primary life-limiting mechanism.

Analysis of experimental data, and development of a discrete element particle-pushing model, have revealed the importance of negative velocity gradients in causing plume widening, and hence overspray grid-impingement. The stability of the cone-jet does not completely describe the likelihood of wide emission, since it is the in-plume interactions that force particles out wide.

Experimental plume-sweeps revealed that the current density is almost Gaussian in nature, whereas the mass flux has a flat-top distribution and sharper drop-off with polar angle than that of a Gaussian over many flow rate and voltage setpoints. The mass flux distribution has much smaller tails, implying less propellant impingement onto the grid than for a Gaussian profile.

A simple plume acceleration model shows the sharp drop-off of mass flux with polar angle leads to negligible grid impingement. Based on the given observations, steady-state on-axis emission does not yield significant mass flux to the grids to limit lifetime. Further studies are needed to confirm the observation of minimal mass flux to the grids, especially in the context of 9-emitter arrays (or larger). Tolerance stack-ups and uncertainties in a multi-emitter array can lead to off-nominal conditions at individual emitters, which may limit lifetime even during steady operation. The presented results do, however, suggest that unsteady operating modes (i.e. commissioning, mode transitions, thrust change commands, etc.) should be carefully considered to accurately estimate lifetime.

High speed microscopy of an EMI-Im cone-jet over a large range of flow rates and voltages could not find any sustained wide-spraying electrospray modes (e.g. whipping, multi-jet). The high conductivity and viscosity of EMI-Im is thought to suppress instabilities that produce wide-spraying modes. The cone-jet was found to be axially sensitive to voltage, most significantly at voltages well above the nominal 1.60 kV extraction voltage. Changing flow rate had a much smaller effect on cone-jet angle, so thrust setpoints are recommended to be changed via flow rate for increased lifetime.

Overall, if setpoint changes are minimized and commanded by flow rate, nominal steady emission is very stable, with negligible mass-impingement on the extractor or accelerator grids. Much longer lifetimes than 60,000 hours are anticipated if emission is kept steady.

If propellant is allowed to accumulate on the emitter it is likely to emit in a very unstable transient mode, pushing large amounts of propellant to the grid. Propellant accumulation, as well as voltage changes, should therefore be avoided.

Models will continue to investigate electrospray phenomenology, seeking to fully resolve high-conductivity fluid and extend the discrete element model to finite-sized droplets that can undergo fission. New experiments will seek improved mass flux and current density resolution. Faster diagnostics are in development to search for high frequency cone-jet oscillations, as well as better-characterization of transient events. Propellant quality (such as contamination or bubble content) and its effect on plume parameters will also be studied.

Secondary Electron Emission (SEE) has not been considered in the present study, but was highlighted as a possible mechanism for failure by Thuppul, Wright, and Wirz. Grid overspray was considered the most likely failure mode, but since new data has shown grid impingement to be negligible during steady emission, attention should now be given to the role electrons may play in electrospray dynamics and lifetime.

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References

