Electrospray Propulsion Time-of-Flight Secondary Ion Mass Spectrometry Diagnostic

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Primary CNF Tools Used: C4500 Odd-Hour Evaporator, Zygo Optical Profilometer, AJA Sputter

Abstract:

Electrospray thrusters are electric propulsion systems offering exceptional thrust-to propellant weight efficiency in scalable form factors. However, system lifetimes are constrained by ion plume interception of downstream electrodes, where high-energy impacts (>1 keV) cause sputtering and secondary ion emission. These secondary ions indicate electrode degradation and electrochemical processes that limit system longevity. An electrospray propulsion secondary ion mass spectrometry diagnostic was developed to investigate ion plume-surface interactions across operational parameters. The system features a single, externally-wetted tungsten ion source with ionic liquid propellants, electron beam-evaporated metallic targets, and linear time-of-flight mass spectrometry. Silver target impacts demonstrate clear target sputtering through detection of silver and silver cluster ions, alongside propellant-related secondary ion markers, enabling comprehensive characterization of lifetime-limiting mechanisms.

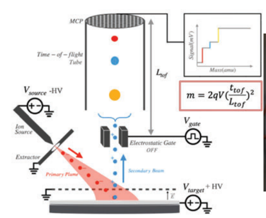
Summary of Research:

Electric space propulsion systems generate thrust by accelerating propellant through electric and magnetic fields, offering superior fuel efficiency compared to chemical propulsion since exhaust velocity depends on applied power rather than chemical bond energy constraints [1].

Electrospray micropropulsion thrusters utilize electrostatic fields to extract and accelerate charged particles from liquid propellant at sharp emitter tips [2,3]. When kilovolt-level potentials are applied between the emitter and downstream extractor electrode, surface tension, electric, and hydrodynamic stresses form a Taylor cone. This induces ion emission through field emission evaporation, accelerating ions to velocities

exceeding 10,000 m/s and generating thrust ranging from nanonewtons to micronewtons per emitter [4,5].

Many electrospray devices employ chemically complex room temperature ionic liquids (RTILs) as propellants, comprising organic cations and anions such as 1-ethyl-3- methylimidazolium tetrafluoroborate (EMI-BF4) and 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-Im) [6,7]. These propellants are attractive for their nonvolatile properties and bipolar operation capability, eliminating



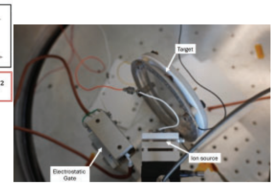


Figure 1 (left): Schematic of the electrospray propulsion TOF-SIMS diagnostic, where the ion source directs the ionic liquid primary beam at the target, where secondary ion emission is induced and directed toward the electrostatic gate and time-of-flight system with an MCP detector. The polarities of the two ion beams are reversed to collect negative secondary ions.

Figure 2 (right): The diagnostic as installed in the vacuum testing facility, including the ion source, the target created via e-beam evaporation, and the electrostatic gate portion of the linear time-of-flight spectrometer.

external neutralizer requirements. This combination makes RTIL electrospray thrusters ideal for missions requiring efficient, compact, low-mass, and low-power propulsion systems [8].

High-energy electrospray plume impacts (>1 keV) induce target surface sputtering, producing secondary ions that interact with electrostatic fields during thruster operation and testing [11]. Understanding their chemical composition is crucial for system performance characterization [12].

A novel electrospray time-of-flight secondary ion mass spectrometry (ESI TOF-SIMS) diagnostic was developed to characterize plume-surface interactions, as shown in Figure 1 and Figure 2. The experimental design features: (a) a tungsten single emitter primary electrospray ion source externally wetted with ionic liquid, (b) a high-voltage target assembly with secondary ion acceleration grid, (c) an electrostatic deflection gate, (d) a time-of-flight tube, and (e) a microchannel plate detector [13].

The primary molecular ion plume impacts a target surface

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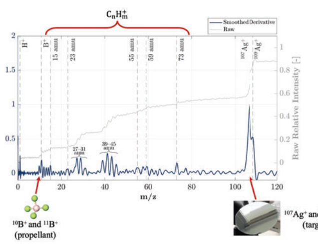
at controlled incidence angles with energies dependent on source and target potentials. High-energy impacts remove secondary electrons, atoms, molecules, and ions from the target surface. Secondary ions of selected polarity are extracted via potential differences between the high-voltage target and grounded acceleration grid, creating a single-polarity, approximately monoenergetic beam that passes through the pulsed electrostatic deflection gate and down the linear time-of-flight tube to the detector.

The target consists of a 100 mm diameter silicon wafer with 100 nm silver deposition via e-beam evaporation using the CNF CVC4500 evaporator. Silver was selected for its two readily identifiable isotopes (^{107}Ag and ^{109}Ag) with nearly equal natural abundances, providing ideal detection and calibration capabilities. Atomically flat, uniform metallic surfaces ensure consistent SIMS signals, as surface topology variations can compromise analysis reliability.

Initial positive secondary ion analysis from a negative electrospray plume impacting a silver target is shown in Figure 3. This spectrum resolves numerous species below 100 amu, notably the hydrogen cation, boron isotopes, and numerous spectral 'families' depicting hydrocarbon-related peaks related to the organic primary impacting ions and/or oil contamination. In addition, peaks at 107, 109, 216 and 324 amu indicate sputtering of the target through detection of silver isotopes and silver cluster ions. Negative secondary ion spectra show the presence of fluorine ion in addition to cyanide and hydrocarbon ions. Initial results show multiple, distinct secondary species that not only prove the capability of the diagnostic but reveal secondary ions that limit the lifetime of electrospray systems [13,14].

Recent work has focused on analyzing secondary ions that form with propellant thin films as the target. The motivation for such work is due to the fact that over time, propellant accumulates on downstream electrodes in electrospray thruster systems. Therefore, at a certain point the secondary ions formed from propellant overspray is independent of the electrode material and entirely dependent on the accumulated propellant. This work has involved producing silver targets utilizing the CNF CVC4500 evaporator, spin coating these wafers with solvent/ionic liquid mixtures and bombarding the thin-film target in the ESI TOF-SIMS diagnostic and analyzing the secondary ions formed. Species from the baseline tests remain present (H+, B+, CnHm+), with additional features that mark the presence of the ionic liquid including the imidazole ring at 83 amu and the imidazole ring with the methyl chain at 96 amu, and most notably the full primary ion cation detection at 111 amu.

Post processing of the thin-film silver target by the Zygo optical profilometer at CNF, as shown in Figure 4, shows sputtering on the order of 100s of nm over the course of ~6 hour beam exposure to the target. The grid-like pattern is a product of the diagnostic mechanical setup, as the primary beam passes through a grounded transparent stainless-steel mesh that maintains the necessary electric fields before impacting the target.



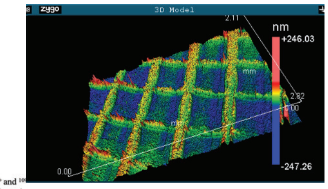


Figure 3 (left): Positive secondary ion mass spectrum from a 4 keV negative EMI-BF4 plume impact with an Ag target, out to 120 amu. The dominant peaks were the silver ion isotopes, with clear signs of the propellant through detection of boron isotopes.
Figure 4 (right): A 3D profile of the target after ion-plume bombardment over the course of 3 hours, showing the sputter depth due to beam exposure.

This information will be crucial in determining sputter rates moving forward.

Conclusions and Future Steps:

A novel electrospray time-of-flight secondary ion mass spectrometry diagnostic successfully characterized plume-surface interactions in electrospray thrusters. Using a tungsten ion source with ionic liquid propellant under vacuum conditions, clear secondary ion emission in both polarities is confirmed, establishing the viability of electrospray TOF-SIMS for thruster analysis. Future work will determine secondary ion origins to distinguish target contamination from primary plume fragmentation, critical for separating intrinsic thruster effects from facility artifacts. Characterizing like-polarity secondary ions requires diagnostic modifications including acceleration stages and target biasing to overcome signal degradation below 2 keV. These enhancements will enable comprehensive analysis across varying operating conditions, propellants, and surfaces, providing insights into plume-surface interactions affecting spacecraft contamination and thruster performance.

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