Plasma-Material Interactions for Electric Propulsion: Challenges, Approaches and Future

IEPC-2019-517

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: The study of plasma-material interactions (PMI) is fundamental to improving the performance and lifetime of many electric propulsion (EP) devices. PMI processes such as ion-induced sputter-ing, sputter erosion, plasma contamination, and secondary electron emission (SEE) have a direct impact on important thruster parameters. Solving these PMI issues is necessary to develop and operate high-power thruster concepts, such as magnetoplasmadynamic (MPD) thrusters and advanced fusion propulsion concepts. Engineering plasma-robust materials may ultimately lead to prolonged thruster lifetimes, higher ∆V for faster orbit transfers, and improved total thruster efficiencies. The EP and nuclear fusion communities have made recent progress in designing plasma-facing materials with advantageous PMI characteristics. Surfaces with complex geometries have shown promising results for the suppression of SEE and ion-sputtering rates. Furthermore, these materials can be used in conjunction with liquid metals for designing regenerative plasma-facing surfaces. At UCLA, several in-situ and ex-situ diagnostics are employed for PMI investigations to provide a complete picture of the plasma and material behavior during exposure. Novel diagnostics for visualizing surface erosion of featured surfaces have been benchmarked using a hollow cathode driven plasma column that delivers plasma densities of order 10¹⁸ m⁻³ to target samples. Results show surface recession and the capture of transient events, such as flaking, via in-situ optical profilometry.

Nomenclature

PMI = plasma-material interactions
SEE = secondary electron emission

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I. Introduction

The study of plasma-material interactions (PMI) is a critical area of research for improving the performance and lifetime of electric propulsion (EP) devices [1] [2]. Mitigating the unwanted effects of PMI can lead to improved thruster parameters such as increased thrust density, propellant ionization efficiency and total thruster efficiency [3]. Designing propulsion-grade electrode materials and investigating the fundamental physics of plasma-surface processes is crucial to many EP device components. To this end, the Plasma & Space Propulsion Laboratory at the University of California, Los Angeles is researching PMI to develop plasma-robust electrode materials using state-of-the-art facilities, along with rigorous theoretical and experimental approaches [4]. Careful material engineering may enable the miniaturization of conventional EP devices (e.g. Hall-effect thrusters), as well as the development of high-power and advanced thruster concepts (e.g. magnetoplasmadynamic thrusters and nuclear fusion propulsion). Recent studies have successfully demonstrated self-healing of materials in conditions representative of those found in plasma thrusters [5]. Self-healing is the ability of a materials to restore its original structural integrity after damage in response to changes in the operating regime, which does not disturb the working capacity of the system. Plasma has also been shown to nucleate nano- and micro- particles directly in the discharge. Direct synthesis and deposition of complex nanostructures (e.g. carbon nanotubes, graphene, and nanoflakes) have been demonstrated in Hall thruster-like plasma conditions [6].

Another important aspect of PMI research for EP purposes is the investigation of facility effects. Secondary electrons emitted from chamber walls and electron transport of these electrons are a common issue in EP testing as they may suppress instabilities and enhance thrust measurements [7]. Sputtering of chamber wall materials is also an unwanted PMI facility effect as deposited materials can alter the diagnostic sensitivities and resulting measurements and lead to the deposition of conductive coatings on dielectric surfaces. PMI is not only important for the effects of ejected particles from wall materials, but also in the design and development of effective beam dump materials for slowing down ions.

In electro spray thrusters, PMI chemistry is very important, specifically secondary electron emission (SEE) due to ion and complex molecule interactions with walls, diagnostics, beam dumps, accelerator and extractor grids. This can limit and degrade the performance of electro spray thrusters. Figure 1 (b) shows a diagram of SEE resulting from propellant interaction with the extractor grid and beam dump in an electro spray setup. Secondary electrons can neutralize and degrade the propellant as they backstream to the emitter as well as alter the plume potential profile [8].

II. Mission Impulse and Plasma-Material Interactions

Improving PMI effects ultimately affects EP mission impulse, $I$. The erosion rate of an EP component material is directly proportional to the thruster lifetime, thus improving the mission $\Delta t$, and improving the mission agility. In many cases, such as in gridded-ion-thrusters, building ion grid optics with more robust, erosion-resistant materials can also improve thrust, $F$:

$$I = \int F dt$$  \hspace{1cm} (1)$$

Aside from increasing thrust, robust lightweight materials can also contribute to reducing the total mass of the thruster, and therefore improve the total efficiency. Developing propulsion-grade electrodes is crucial to enabling research towards advanced propulsion concepts where extreme plasma conditions such as high temperatures, current densities and plasma densities, particularly for pulsed modes, cause degradation of the materials in very short time scales. In order to develop such materials, the plasma-surface physics and chemistry needs to be well understood and processes such as ion recycling and material ablation should be addressed. Figure (1) shows representative thrust profiles for different mission types. In one case, a typical EP mission has continuous decreasing thrust levels as the spacecraft moves away from the Sun and in a more flexible mission scenario, the thruster can achieve high-thrust maneuvers as well as low-thrust maneuvers for orbit raising or low-thrust orbit changes [9]. Resolving PMI challenges can therefore enable missions with higher agility for further and longer missions. Figure (2) shows where different types of EP thrusters lie on the specific impulse vs thrust/power ratio on equi-efficiency curves ranging from total thruster efficiency $\eta_T = 0.2 - 1.0$ according to:

\begin{align*}
\end{align*}

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where $T$ is thrust, $P$ is power and $\eta_T$ is thruster efficiency. This figure is adapted from Ref. [10]. Each type of thruster has several PMI issues which are critical to improving their performance. It is important to note that fusion thrusters cover a large region in the Isp to thrust/power space in the case where the thruster is fusion-enhanced (power out is larger than the power into the system), therefore designing electrode with beneficial PMI properties is applicable to a large range of EP thruster concepts.

Increasing thrust and thruster efficiency is key in developing high-power EP systems for missions which require high delta-V maneuvers, such as interplanetary missions or beyond Solar System missions. These missions require long operational times, and improved thruster reliability. PMI research can be beneficial to advancing current EP performance. Missions to Mars can require $\Delta V$s of up to 30 km/s whereas beyond Solar System missions may require up to 70-80 km/s maneuvers. These high $\Delta V$s can be achieved using magnetoplasmadynamic thrusters, or advanced fusion concepts.

![Representative thrust profiles for EP mission types. (Left) EP mission for inter-planetary destination showing decreasing thrust as the spacecraft moves further from the Sun where solar power is the main power source, including thruster off times. (Right) Mission with high and low $\Delta V$ capabilities required for high-agility Earth orbiting missions (e.g., for defense applications).](image)

**Figure 1.** Representative thrust profiles for EP mission types. (Left) EP mission for inter-planetary destination showing decreasing thrust as the spacecraft moves further from the Sun where solar power is the main power source, including thruster off times. (Right) Mission with high and low $\Delta V$ capabilities required for high-agility Earth orbiting missions (e.g., for defense applications).
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**Figure 2.** Specific impulse versus thrust/power ratio for conventional EP systems (arcjet, ion, Hall, electrospray) and advanced EP thruster concepts (magnetoplasmodynamic (MPD), field-reverse configuration (FRC), fusion). Fusion thrusters lie in the top corner of the parameter space and fusion-enhanced thrusters cover the parameter space below fusion and above conventional EP systems. The fundamental PMI processes for each propulsion type are indicated [10].

### III. Physics of Plasma-Material Interactions

The two PMI processes of major interest to EP applications are secondary electron emission (SEE) and ion-induced sputtering which often leads to important effects such as plasma cooling, sheath modification, plasma contamination, and surface erosion [11] [12] [13]. It is important to make the distinction between sputtering and erosion: sputtering is the mechanical removal and ejection of surface atoms due to momentum exchange between incoming particles and the material surface, while erosion is the measure of surface recession of a material during sputtering. A grooved surface for example may have low sputtering yield compared to a planar surface due to particle trapping in the surface features. This reduce sputter yield can reduce plasma contamination but the erosion rate or surface recession may very well be the same as that of a planar surface. Therefore, reduced sputter yield may reduce the total mass of EP systems, and maintain or improve plasma performance. However, to improve the lifetime of EP thrusters it is important to design materials with low erosion rates. Materials with low SEE yield properties are also desirable in the context of EP because of reduced bulk plasma cooling by the introduction of cold electrons, though one must ensure that sheath modification does not lead to unwanted increases in erosion and/or sputter yield. Figure 3 (a) shows the main PMI processes occurring at the surface interface, and Figures 3 (b) and (c) show the processes of ion-induced sputtering and SEE.
Inside the plasma bulk, maintaining quasi-neutrality prevents large, disruptive electric fields from forming. However, near a bounding surface, the more mobile electrons reach the wall much more rapidly than the ions. This creates a potential drop, $\phi_b$, which retards the further flow of electrons to the wall while also accelerating ions to it until a current balance is reached. The potential drop is typically confined to a small region near the wall such that quasi-neutrality is maintained in most of the bulk. When the ion and electron current to the wall are equal, the sheath (“floating”) potential is given by

$$\phi_{sh} = \frac{kT_e}{e} \ln \left( \sqrt{\frac{M}{2\pi m}} \right)$$  \hspace{1cm} (3)

where $T_e$ is the electron temperature, $m$ and $M$ the electron and ion masses, respectively, and $k$ is Boltzmann’s constant. If electron emission is accounted for, however, Hobbs and Wesson showed that the sheath potential decreases based on the SEE yield, $\gamma$, or the ratio of emitted secondary electrons to incident primary electrons [14].

$$\phi_{sh} = \frac{kT_e}{e} \ln \left( 1 - \gamma \right) \sqrt{\frac{M}{2\pi m}}$$  \hspace{1cm} (4)

Because of the decrease in the sheath potential drop, more primary electrons can reach the wall, leading to a reduction in the average electron temperature in the plasma bulk. This in turn decreases the ionization rate, degrading the performance of plasma devices. On the other hand, low SEE materials can increase the sheath potential, which may provide higher acceleration for the incident ions and thus increased sputter yield. Therefore, careful consideration of these competing effects must be considered.

**Figure 4:** Plasma potential in the sheath region for a floating wall without SEE (left) and with SEE (right).

**A. Secondary Electron Emission**

SEE occurs when electrons with sufficient kinetic energy impact a solid surface [15]. The emitted electrons are secondary electrons and the bombarding electrons are primary electrons. SEE depends on the primary electron energy, the target material work function, and the primary angle of incidence. There are two types of secondary electrons: backscattered and true secondary electrons. Backscattered electrons are reflected primary electrons which can be elastically scattered or inelastically scattered, and true secondary electrons are electrons which are ejected from the surface atoms. These typically have energies $< 50$ eV while backscattered electrons have energies up to the incoming primary electron energies. Figure (5) shows a schematic of secondary electrons generated by primary electron impact onto a material surface.

**Figure 5.** Schematic of SEE products: true secondary electrons, and elastically and inelastically scattered.
SEE is important in the context of EP because cold emitted electrons cool down the bulk plasma therefore reducing its performance in magnetically unshielded Hall thrusters. Additionally, SEE contributes to anomalous electron transport and may reduce propellant utilization efficiencies [16] [17] [18] [19] [20]. Additionally, SEE can cause increased power losses to the chamber walls [14]. If the heat flux to the wall, $Q$, is calculated across the plane through $x = 0$, it will include primary electrons which carry an energy of $2kT$ due to thermal effusion, primary ions which carry energy $E$, plus the energy gained by falling through the sheath potential expressed in Equation (4). Then:

$$Q = n_0 v_0 \left[ \frac{2kT}{1 - \gamma} + \frac{kT}{2} + kT \ln \left( \frac{1 - \gamma}{2\pi m M} \right) \right]$$  \hspace{1cm} (5)$$

where $n_0$ and $v_0$ are the ion density and ion velocity respectively. Figure 3 shows how the power flux loss to the wall increases with increased SEE yield coefficient of the wall material for parameters similar to those of a magnetically unshielded Hall-thruster plasma, where electron temperatures are on the order of $\sim 10$ eV, and the SEE yield coefficient often approaches unity for graphite or boron nitride channel wall materials.

![Figure 6](image-url)

**Figure 6.** The variation of heat flux loss to the wall versus SEE yield coefficient for electron temperatures of 1 eV, 5 eV and 10 eV. As the SEE yield coefficient approaches unity, the heat flux loss to the wall increases dramatically according to Equation (5).

**B. Ion-induced Sputtering**

Ion-induced sputtering is the most significant source of wear in gridded ion thrusters [21] [22] [23] [24]. There are five failure modes related to grid erosion due to ion-sputtering: accelerator grid structural failure from CEX ions sputtering downstream of the accelerator grid, grid electrical shorting, electron back streaming due to enlargement of the accelerator grid apertures, sputtering of the screen grid from direct impingement of discharge chamber ions, and accelerator grid failure due to direct ion impingement from defocused beamlets resulting from material depositing on the screen grid aperture. The most significant failure mode is due to currents of CEX ions generated downstream of the accelerator grid impacting the accelerator grid and causing erosion over time. Figure (7) shows SEM images of the NSTAR gridded ion thrusters after $\sim 30,000$ hours of operation and the effect of ion-induced sputter erosion on the accelerator grid [2]. Charge exchange (CEX) ions are generated downstream of the accelerator grid and cause a ‘pits and groove’ erosion pattern, resulting in holes which can be seen on the upstream surface of the grid. In an ion thruster, the erosion rate of a grid optic is proportional to the ion fluence which is linear in time, but may not be linear with thrust. As the perveance limit is approached, localized erosion takes place which has nonlinear effects on the thrust performance of the system.
Another phase during which MPDs suffer major erosion is during thermionic attachment which occurs when the heated cathode plasma is ionized. A magnetic field is created by the current returning to the power supply through the cathode. The self-induced magnetic field and plasma current produce a Lorentz force which pushes the plasma out of the engine, creating thrust. Exhaust velocities can reach up to ~100,000 m/s and ~100N thrust levels can be achieved [27]. A major issue in MPDs however is evaporative erosion of electrode materials. Major erosion occurs during the startup phase of an MPD when the cathode is still cold and a spotty discharge exists. The current densities from arcing onto the cathode can be on the order of ~10^{12}A/m^2. A favored spot on the cathode which is usually a protrusion of the downstream is significantly higher for larger beamlets operating closer to the perveance limit.

For high plasma densities, thrust scales linearly and the screen grid erosion increases with increasing plasma density via direct ion impingement. The accelerator grid however does not erode linearly as the plasma scales up due to the CEX process. In the lower plasma density case, there are fewer CEX ions generated downstream and upstream of the accelerator grid, resulting in less erosion of both the accelerator and screen grid.

Another important PMI process in ion thrusters is electron backstreaming due to ion grid optic wear. This is caused by the random flux of high energy electrons from the thruster’s beam that flow back into the main discharge chamber by overcoming the potential barrier established by the accelerator grid. Minimizing this effect is important because electron backstreaming uses valuable spacecraft power and degrades the thruster life [25].

Ion-induced erosion of hollow cathodes is also a PMI challenge which has been observed and studied since the late 1980s [26]. Energetic ion-bombardment limit the mission capability and lifetime via sputter erosion of surfaces exposed to high current hollow cathode plumes. The production of these energetic ions has long been observed and discussed and several explanations for the source of their production have been proposed. One study suggests that ion acoustic turbulence in the cathode plume caused by a high electron Mach number may be a significant contributor [27]. Other studies and theoretical simulations instead have shown that the keeper face of a LaB_{6} cathode shows erosion rates due to ion falling through the sheath potential alone, and that erosion rates were related to operating conditions known to result in energetic ions. [28] [29]

**C. Advanced Electric Propulsion Concepts**

Advanced propulsion concepts with PMI implications include magnetoplasmadynamic (MPD) thrusters and nuclear fusion propulsion systems, such as the Z-pinch concept [30]. In MPDs, an electric arc is struck between the anode and the cathode. As the cathode heats up, electrons are emitted and the injected has is ionized. A magnetic field is created by the current returning to the power supply through the cathode. The self-induced magnetic field and plasma current produce a Lorentz force which pushes the plasma out of the engine, creating thrust. Exhaust velocities can reach up to ~100,000 m/s and ~100N thrust levels can be achieved [27]. A major issue in MPDs however is evaporative erosion of electrode materials. Major erosion occurs during the startup phase of an MPD when the cathode is still cold and a spotty discharge exists. The current densities from arcing onto the cathode can be on the order of ~10^{12}A/m^2. A favored spot on the cathode which is usually a protrusion of dielectric impurity gives way to a strong electric field which eventually breaks down [31]. Breakdown causes local overheating leading to material evaporation and a small crater can be formed during this spot. The erosion rate is proportional to the spot current and rates can be as high as ~10μg/C. Another phase during which MPDs suffer major erosion is during thermionic attachment which occurs when the thoriated cathode is heated up and glowing. Solutions to these PMI issues include using deoxygenating devices, liquid metal coated cathodes, and propellant mixing and doping to deposit lower work function materials on the cathode.

In order for fusion thruster concepts such as the Z-pinch thruster to become viable propulsion systems, propulsion grade electrodes and PMI solutions must be investigated. The Z-pinch thruster is a design with no external magnetic field coils. The self-generated magnetic field confines the fusing plasma and electrodes supply the electrical current directly to the plasma. The Z-pinch configuration therefore confines and compresses a plasma to achieve fusion energy
release. One of primary challenges is to develop electrode materials which can withstand plasma contact without eroding and without degrading plasma properties. The plasma current can be up to 200 kA with plasma densities of up to \(10^{23}\) m\(^{-3}\) and current densities at the electrodes of up to 4 MA/m\(^2\) – 7 GA/m\(^2\) \cite{32}. The material issues range from sputtering to exfoliation, sublimation and vaporization, extreme thermal heat loading and neutron interactions. The thruster embodiment of the Z-pincher thruster needs to ensure high-performance and long-life in a mass-constrained and volume constrained environment. Also, as with other space devices, the electrodes cannot be replaced in-situ.

Figure 8. (a) Magnetoplasmadynamic thruster operating on argon propellant at Princeton University \cite{33}. (b) Similar coaxial configuration of a Z-pincher thruster concept with shear flow stabilization to suppress plasma instabilities in the Z-pincher arc. Image derived from \cite{32}. One of the primary challenges is plasma attachment to the cathode and anode of the thruster which lead to extreme erosion and to arc plasma contamination.

### IV. Complex surfaces as a solution to PMI challenges

In recent studies it has been shown that materials with complex nano-, micro- and even mm-sized features can reduce both SEE and ion-induced sputtering by trapping emitted particles in the regions between their cavities. These materials include fibrous velvets, grooved surface, irregularly roughened surfaces and porous surfaces \cite{34} \cite{35} \cite{36} \cite{37} \cite{38} \cite{39}. Jin et al \cite{36} showed experimentally that the SEE yield of carbon velvets are reduced by up to 65% compared with a planar surface, and Huerta et al \cite{40} have shown that a porous material can also reduce SEE yield values by up to 75% compared with a planar surface via a trapping mechanism. Li et al \cite{41} \cite{42} showed that micro-architected molybdenum surfaces have a sputtering yield reduced by 45% compared with a planar surface, but approached the planar surface value as the features were eroded away. For this reason, volumetrically porous materials have been recently considered. By having a volumetrically structured bulk material, the sputtering reduction by geometric means is distributed throughout the interior of the material as opposed to being isolated on the surface. In addition, sputtering occurring inside the foam mesh network causes non-linear sputtering deposition processes that may provide a lower thickness erosion rate. Previous computational work with high energy sputtering of nano-foams has predicted an effective sputtering yield reduction \cite{43}.
Figure 9. Three SEM images of featured surfaces are shown (from left to right): carbon velvet with 1.5 mm long fibers, aluminum foam with 40 pores per inch, and nano-sized tungsten foam resulting from energetic helium ion bombardment.

As thruster research trends towards higher powers (100 kW to 10 MW) and advanced concepts such as MPD thrusters and fusion thrusters, the need for renewable electrode systems increases. At high temperatures and current densities, the recycling of evaporated and sputtered cathode material in the plasma becomes important. Sputtered atoms and molecules are ionized in the near-cathode plasma and then return as ions to the cathode followed by surface recombination. This cycle then may repeat itself resulting in an active ion recycling system. In the case when the recycling of high vapor pressure materials in the plasma is less than 100%, the material losses could be replenished by feeding liquid metal through the cathode by using materials such as lithium or tin and a porous material to flow the liquid through. Volumetrically porous foams therefore are ideal structures for studying not only reduced SEE and sputtering yield, but also for flowing liquid metals through to develop renewable cathode concepts.

Figure 10. (a) Schematic of a high current density plasma attachment to a cathode surface. Ion-atom recycling occurs in the near-cathode plasma region via sputter-redemption, where sputtered or vaporized atoms and molecules are ionized in the near-cathode plasma and then redeposited via the sheath potential. (b) A possible cathode concept that uses liquid metal infiltrated in a volumetrically porous solid matrix to replenish cathode material that is not effectively recycled via sputter-redemption.

V. Plasma-Material Interaction Research at UCLA

UCLA’s Plasma & Space Propulsion Laboratory conducts research dedicating to investigating PMI processes computationally and experimentally. Computational efforts are summarized by Wirz, et al. [4]. For experimental efforts, a list of available intrusive and semi-intrusive diagnostics available in UCLA’s Plasma & Space Propulsion Laboratory is given in Table I. The majority of PMI experimental efforts are conducted in the Plasma-interactions (Pi) facility described in Figure 11. The Pi facility consists of a LaB$_6$ hollow cathode plasma source coupled to an axial magnet system for directing a focused plasma to a target sample. The sample is biased negative relative to ground potential (anode) to enable energetic ion bombardment for sputtering and erosion studies. The sample is biased positive with respect to ground to investigate electron heating.

<table>
<thead>
<tr>
<th>Type</th>
<th>Diagnostic</th>
<th>Measured Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-intrusive</td>
<td>Quartz Crystal Microbalance (QCM)</td>
<td>Differential sputtering rate, sputtering yield</td>
</tr>
<tr>
<td></td>
<td>Long Distance Microscope (LDM)</td>
<td>Surface visualization, height map</td>
</tr>
<tr>
<td></td>
<td>Optical Emission Spectroscopy (OES)</td>
<td>$n_e$, $T_e$, and $n_e$ of sputterant species</td>
</tr>
</tbody>
</table>
Laser Induced Fluorescence (LIF) | Ion/neutral velocity distribution function
---|---
Laser Absorption Spectroscopy (LAS) | $n_\text{in}, T_\text{in}$ of sputterant species

<table>
<thead>
<tr>
<th>Semi-intrusive</th>
<th>Ex-situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langmuir Probe</td>
<td>SEM/EDS/TEM/XPS/Laser Profilometry</td>
</tr>
<tr>
<td>Faraday Probe</td>
<td>Comprehensive surface mapping</td>
</tr>
<tr>
<td>Emissive Probe</td>
<td></td>
</tr>
<tr>
<td>Retarding Potential Analyzer</td>
<td></td>
</tr>
</tbody>
</table>

Table I. Intrusive and non-intrusive plasma and material diagnostics in UCLA’s Plasma & Space Propulsion Lab.

![Figure 11](image)

Figure 11. Schematic of plasma-interactions (Pi) facility at UCLA.

The magnetic field near the target was designed to enable diagnostic access to the near-target plasma region where sputtering and redeposition processes are concentrated. The operating conditions of the Pi plasma experiment have been well characterized in past experiments [41] [44]. The plasma conditions used for the series of testing are reproduced from Li et al. in the Table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
<td>$10^{18}$ m$^{-3}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>7 eV</td>
</tr>
<tr>
<td>Ion energy</td>
<td>40 to 400 eV</td>
</tr>
<tr>
<td>Ion flux to target</td>
<td>$10^{17}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Target area</td>
<td>$\approx 1.8$ cm$^2$</td>
</tr>
</tbody>
</table>

Table II. Plasma parameters used for Pi experiment with an aluminum foam target.

An experiment has been conducted using the Pi facility to explore the sputter erosion of volumetrically porous materials and to determine its overall SEE yield properties. The erosion resistance of a material is characterized by the sputtering yield, a statistical measure of the number of ejected sputterant atoms per incident ion. The two primary techniques used to measure the sputtering yield in the Pi facility are the weight loss method and quartz crystal
microbalance (QCM) method as described in Ref. [41]. The authors found that the sputtering yield of a structured molybdenum surface reduced the sputtering yield by as much as 40% initially, but eventually approached the yield of flat molybdenum as the surface features are eroded away. This result motivated the investigation of foam samples for improved sputtering resistance.

Figure 12. The sputtering yields of (a) structured molybdenum [41] and (b) an aluminum foam sample normalized to the flat material sputtering yield value during plasma exposure.

Figure 12 shows the normalized sputtering yields of the structured molybdenum sample presented in Ref [41] as well as results of an aluminum foam sample. The sample is an Al foam with 20 pores per inch. The Al side is bombarded by argon ions. For the Al foam, the QCM was positioned at a fixed location of 30° relative to the target normal and measured a differential sputtering rate. This differential sputtering rate is combined with the ion current measurement as described in Ref [41] to produce a differential sputtering yield. With the assumption that the angular sputtering profile is constant at all angles (an overestimation since 30° should have a larger differential yield), the total sputtering yield is estimated and plotted in Figure 12. It can be seen that the sputtering yield for the Al foam is reduced at all times compared to the flat aluminum value. While the featured molybdenum sample eventually erodes into a flat sample, the volumetrically porous aluminum foam retains a reduced sputtering yield throughout the entirety of the ion-bombardment experiment.

To visualize the erosion of the Al foam sample, a novel in-situ long distance microscopy (LDM) technique which uses focus-variation to reconstruct real-time composite images of an evolving surface was used. The LDM diagnostic

Figure 13. Composite images of an aluminum foam generated using in-situ LDM data and related height maps are shown for varying ion fluence during energetic argon ion bombardment.

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enables the visualization of surface changes such as foam ligament diameter reduction and flaking, which can cause plasma contamination in an EP device. Height maps are generated to evaluate the erosion rate of the foam in conjunction with the QCM sputtering yield measurements. In the case of an Al foam surface, the erosion rate is comparable to that of a planar surface while the sputtering yield was shown to be reduced. While reduced sputtering is beneficial to reducing plasma contamination, further development is required to design materials with reduced erosion rates for prolonged electrode and thruster lifetimes.

VI. Conclusions
As summarized in Figure 14, PMI processes have major implications on the performance and lifetime of EP devices ranging from conventional, low thrust density Hall and ion thrusters, to advanced high thrust density technologies such as MPD thrusters and fusion thrusters. Additionally, improved understanding of PMI is needed to understand EP facility effects, primarily through secondary electron emission and ion-induced electron emission. The processes of plasma contamination and plasma cooling dominate the material effects on a plasma, whereas ion sputtering and secondary electron emission dominate the plasma effects on a material. For many types of thrusters, such as gridded ion thrusters, a main challenge is developing propulsion-grade electrode materials and grid materials which can withstand extreme plasma conditions and are erosion resistant. In recent experiments, it was found that materials with volumetrically porous structures are effective at capturing secondary electrons and sputterants in their cavities, thus resulting in reduced sputter yield and SEE yields. These materials are therefore promising candidates for designing electrode surfaces due to reduced sheath modifications and plasma contamination. Leveraging PMI research from the magnetic fusion confinement community can also provide valuable insight when designing renewable plasma-surface systems such as flowing liquid metals through porous structures.

![PMI Processes Diagram](image)

**Figure 14.** Summary diagram of PMI processes on different types of EP thrusters and testing. Note that “Secondary electron emission” includes the effects of electron-induced and ion-induced electron emission.

VII. Acknowledgments
This effort was supported by AFOSR Award Nos. FA9550-14-10317 (UCLA Subaward No. 60796566-114411) and FA9550-16-1-0444. The authors would like to thank Mitat Birkan, Michael Holmes, and Justin Koo of U.S. Air Force for insightful discussions and resources on the topic of plasma-material interactions for EP devices, particularly related to Figure 2.
VIII. References


