# Field Emitter Cathodes and Electric Propulsion Systems

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**Abstract**

Replacing hollow and filament cathodes with field emitter (FE) cathodes could significantly improve the scalability, power, and performance of some meso- and microscale Electric Propulsion (EP) systems. This article discusses the motivation and challenges of integrating of FE and Electric Propulsion systems. The demands on cathode performance and lifetime and the propulsion system environments are described in this article. The FE cathode technologies which are currently believed to be the most compatible with the plasma environments of EP systems and the further advances required are also discussed.

## 1. Introduction

There is considerable interest now in microscale spacecraft to support robotic exploration of the solar system and characterize the near-Earth environment. Three classes of microscale spacecraft have been identified: Class I (10-20 W, 10-20 kg, 0.3-0.4 m), Class II (1 W, 1 kg, 0.1 m), which is sometimes referred to as nanoscale spacecraft, and Class III (<<1 W, << 1 kg, 0.03 m), which is also referred to as picoscale spacecraft.[1] Microscale spacecraft will enable the development of multiple, distributed spacecraft systems to perform three-dimensional mapping of fields and particles with a resolution and flexibility unobtainable with a single, larger spacecraft. In addition to the mapping of tensor fields, microscale spacecraft mission scenarios have been envisioned where, rather than launching a single large spacecraft, the mission is accomplished by a fleet of several smaller microscale spacecraft, with the scientific payload distributed among the micro-craft to reduce mission risk. Loss of one of these spacecraft would not jeopardize the entire mission. A fleet of several microscale spacecraft, possibly in connection with a larger "mother"-spacecraft, could also increase mission flexibility. Smaller micro-craft could be placed on different trajectories around the target planet and provide an almost instantaneous, global survey of the target. A mother-craft could also release smaller micro-craft to perform high-risk operations. In one example, a close-up investigation of Saturn's ring objects has been envisioned with a swarm of microscale spacecraft descending into the ring environment while the mother-craft, providing high-data rate communication to Earth via a large high-gain antenna, may cruise at a safe distance.

The fuel savings from the use of high specific impulse (thrust/propellant flow rate>1000 s) electric propulsion systems enables more difficult planetary missions with smaller launch vehicles, a critical capability in today's environment of cost-constrained exploration missions. Low required propellant mass will reduce overall spacecraft size and weight and high-specific impulse electric propulsion technology thus represents an obvious design approach for microscale spacecraft. The challenge is to arrive at a working, miniature electric propulsion system which can operate at much lower power levels than conventional electric propulsion hardware, and meets the unique mass, power, and size requirements of a microscale spacecraft. In addition, this technology may be used for ultra-fine attitude control on larger spacecraft, such as future interferometry missions or future inflatable spacecraft. These spacecraft will be required to offset solar disturbance torques, requiring minute thrust adjustments. In the case of inflatable spacecraft, like those proposed for mission concepts such as Arise and Space Solar Power, these propulsion modules may have to be integrated with the inflatable structure itself, necessitating the need for small, extremely light-weight propulsion systems. Micro-electromechanical systems (MEMS)-based technologies including thrusters, valves, and control electronics may be integrated into a single chip or a 3-D stack of chips. Integration approaches like this are being implemented at the Jet Propulsion Laboratory. Larger scale inflatable spacecraft will also require mesoscale Hall or ion thrusters which provide 1-10 mN of thrust at power levels < 300 W with discharge chamber diameters smaller than 50 mm (Hall thrusters) or 60 mm (ion thrusters).

Some electric thrusters being miniaturized require a cathode to provide electrons for propellant ionization and/or ion beam neutralization. The positive ion beam emitted by the thruster must be accompanied by an electron beam to prevent spacecraft charging. Electrostatic thrusters are being developed to operate between 10s of mW and 500 W. For the small scale size and power objectives for electric propulsion system miniaturization, FE cathodes have demonstrated much higher efficiency, smaller dimensions, and lower system complexity than filament and hollow cathodes. Filament, thermionic, and hollow cathodes require heaters and propellant feed systems which place lower limits on their power and size scalability. Filament cathodes consume 20 W/cm and 0.2 –10 W/mA with short lifetimes. *Thermionic cathodes have demonstrated 1.5 W/mA without propellant.*[2] *State-of-the-art 1/8" hollow cathodes have demonstrated 0.12 A with 0.1 mg/s of xenon and 2.4 W consumed by the keeper with an anode voltage of30 V.*[3] A cesium hollow cathode which demonstrated 10 W/mA, has been used with cesium field emission electric propulsion (FEEP) systems. A FE cathode has demonstrated 120 mA at <1 mW with no propellant or heater. Some microscale spacecraft proposed will have less than 100 mW of power. Compatible FE cathodes may enable the use of EP systems on these spacecraft.

The primary concerns with integrating FE cathodes with EP systems are space-charge limited emission and cathode lifetime in the plasma environments generated by the propulsion systems. Typically FE cathodes are operated in a close-spaced triode or diode configuration with one electrode as the anode. In an EP system the FE cathodes will have to operate in a diode configuration with a gate electrode and the local plasma providing a virtual anode. The space-charge current limit depends on the plasma density and temperatures, and electron beam energy and current density. The cathode lifetime will be limited because it will be subjected to constant ion bombardment. The self-generated ion population originates near the cathode when the electrons emitted by the cathode ionize ambient neutrals. These ions will be accelerated to the cathode gate electrode or the emitting area of the cathode. The energy of these ions will depend on the potential where they are created. This ion flux depends on the cathode current, cathode potential, and local pressure. The second ion population is generated near the thruster. Slow ions and fast neutrals result from charge-exchange collisions between the fast ions accelerated by the thruster and the slow ambient neutrals. Ions are also generated in the discharge chamber of an ion thruster. The cathodes used in the ion thruster discharge chamber will be subjected to this third flux of ions. Some of these ions will be accelerated to the cathode between the potential where the ion is created and the cathode potential. This charge-exchange and discharge ion flux depends on the thruster discharge current, discharge voltage, and local pressure. This ion rich environment can cause permanent changes in the structure of the emitting surface and temporary changes in the cathode work function, severely affecting the cathode performance.

In the following section of this paper the approach to integrating these technologies is discussed. Meso- and microscale thrusters which could benefit from a compatible FE cathode, the cathode requirements, and the cathode environment in these systems are described. Cathode candidates which currently seem to be the most compatible with EP systems and required advances in FE cathode technologies are also presented.

## 2. Meso- and Microscale Electric Propulsion Systems

In this section, the configuration and performance of several meso- and microscale electric thrusters are described, the cathode performance requirements are presented, and the cathode environments are discussed. Mesoscale ion and Hall thrusters have the advantage of higher thrust levels and an inert propellant. Colloid and field emission thrusters have the advantage of scalablility in size and power to be compatible with microscale spacecraft. The majority of the mesoscale and microscale thrusters have not yet been developed; the performance of larger systems are discussed in this section with performance objectives for the miniature systems. However, it is obvious that each of these systems will be radically improved with a compatible FE cathode. Tables are presented at the end of the section describing the performance of the some systems developed which are both small and efficient, the cathode environment, and state-of-the-art cathode performance.

### 2.1 Mesoscale Ion Engine

An ion engine has three major components as shown in Figure 1: (1) the discharge chamber, (2) the ion optics and (3) a neutralizer cathode. Propellant injected into the discharge chamber is ionized by electron bombardment in a low pressure discharge. Permanent magnets oriented axially near the anode trap the electrons and impede their flow to the anode. The ion optics are composed of two multi-aperture grids which are biased to accelerate and focus ions which drift into the interelectrode gap. The neutralizer cathode produces electrons to neutralize the ion beam. Modeling has shown that the ionization efficiency of the discharge chamber is unacceptably low if the device scale is too small, primarily because the higher surface-to-volume ratio results in excessive plasma losses to the walls. Current research is therefore focused on mesoscale thrusters with MEMS components, rather than microfabricated engines.

There are several approaches to plasma production in small **engines (need refs).** Mesoscale ion thrusters were developed to operate on cesium with considerable success; however, xenon propellant is preferred over cesium because of its toxicity. Cesium ion thrusters with 2.54 cm diameter discharge chambers demonstrated 10 μN/W with 0.1 mN at 10 W.[4] More recently, a xenon ion thruster with a 5 cm diameter discharge chamber demonstrated 2.2 mN and 2300 s at 49% thrust efficiency and 50 W of power.[5] The performance of the 5-cm thruster is described in Table 1. The approach described here uses a conventional electron bombardment discharge chamber with field emitter cathodes, conventional chemically-etched metal grids or MEMS grids[6] and a field emitter neutralizer. The mesoscale engines under investigation are on the order of 1 to 5 cm in diameter and will operate at power levels of 10 to 300 W. The desired operating characteristics are an exhaust speed of 36 km/s (specific impulse of 3600 s), thrust levels of 0.5 to 5 mN, an efficiency of 50 % and lifetimes of up to 6000 hours.

A FE cathode compatible with an ion thruster could significantly improve the system efficiency. The requirements on a discharge cathode is emission of up to 1 A reliably over 6000 hours into xenon gas with a pressure of up to $10^{-4}$ torr and a plasma density of $10^{11}/cm^3$. The neutralizer cathode must also operate for up to 6000 hours and be capable of emitting up to 40 mA in the environment near the exit plane of the thruster, where xenon gas pressures may be as high as $10^{-5}$ torr and the charge exchange ion current densities should be less than 0.004 $mA/cm^2$. The charge-exchange ions will be accelerated through approximately 20 V between the plasma and the cathode gate electrode.

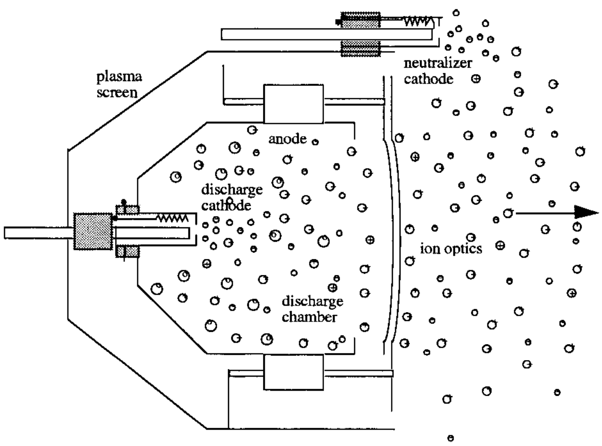


**Figure 1 Ion thruster configuration.**

**2.2 Mesoscale Hall thruster**

A Hall thruster is an electrostatic propulsion device which also ionizes the propellant by electron bombardment, like the ion thruster. A cross-section of a Hall thruster is shown in Figure 2. Propellant is injected through the anode into the discharge chamber. A single cathode is used to emit electrons which ionize the propellant and neutralize the ion beam. The potential applied between the anode and cathode creates an axial electric field to accelerate the ions. Inner and outer electromagnets create a radial magnetic field with large gradients near the physical exit plane of the thruster. The electrons enter the discharge chamber and become confined by the magnetic field in an azimuthal drift towards the anode. Propellant is ionized in the electron cloud. The ions are primarily accelerated in the discharge chamber by the axial electric field to generate thrust. Because of the high electron density in the ionization and acceleration region, the ion current density is not space-charge limited like the ion thruster. Therefore, Hall thrusters can deliver the same thrust from a more compact system.

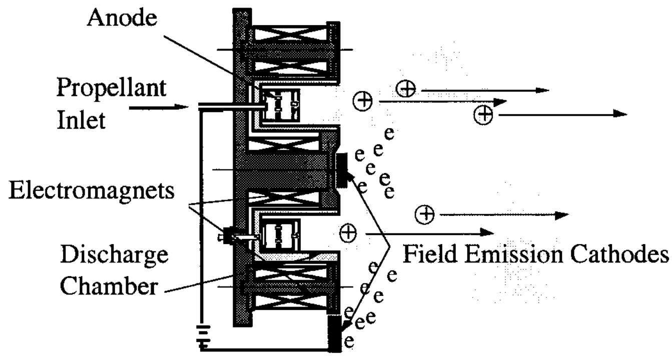


**Figure 2 A cross-section of a Hall thruster.**

Hall thrusters have been optimized to operate at 1.5 -3.0 kW and are currently being scaled down to mesoscale systems which are optimized to generate 1-10 mN of thrust. In deriving scaling relationships for a Hall thruster, Khayms et al. maintained a constant ratio of the mean free path of each of the species to a characteristic length scale of the thruster. Higher pressures, current densities, and magnetic field strengths are then required to reduce mean free paths in the discharge chamber and maintain the plasma discharge as the size of the thruster is reduced. The X-40,[7] D-32,[8] and a 50 W[9] Hall thruster fall into the mesoscale thruster category. Xenon is the preferred propellant for these systems because of its high mass, relatively low ionization energy, and inert nature. The X-40 has a 40 mm discharge chamber diameter. It demonstrated 7.43 mN of thrust at 100 W (150 V, 0.67 A) and 0.74 mg/s to generate **1020 s specific** impulse (ion velocities of ~10,000 ms/) at 37 % efficiency (not including the cathode power and propellant). At 200 W and 14.5 mN, the thruster operated at 48 % efficiency. The lifetime of this system was projected to be 850 hours. It could be improved to 2000-3000 hours by employing more sputter resistant materials. The D-32, with a 32 mm diameter discharge chamber demonstrated 4.3 mN at 75.6 W (120 V, 0.63 A) and 0.6 mg/s at 20 % efficiency. At 172 W (200V, 0.88 A) and 0.9 mg/s, the D-32 operated at 27 % efficiency. The D-32 and X-40 both used electromagnets to facilitate magnetic field optimization at each operating point. Permanent magnets were used in the 50 W thruster developed with a 3.7 mm discharge chamber because of its small size and potentially high operating temperatures of the electromagnets. While medium scale Hall thrusters with 100 mm discharge chamber diameters require magnetic fields of 300 Gauss, the 50 W thruster required magnetic fields exceeding 5000 Gauss. This thruster operated at 100 W (250 V, 0.38 A) and 0.021 mg/s to generate 773 s at 6 % efficiency. The performance of this thruster was limited, in part, by the magnetic system used. The magnetic field configuration could not be optimized at each operating point and the high operating temperature of the thruster could have affected the performance of the magnets. The thrust efficiency also tends to decrease with decreasing discharge chamber diameter.

Miniaturization of the Hall thruster seems to be limited to a 40 mm discharge chamber to achieve at least 30 % efficiency. These thrusters were tested with a hollow cathode and the thruster performance described does not consider cathode power and propellant consumption. Consideration of the hollow cathode performance also decreases the efficiency of the system by several percent.

A field emission cathode compatible with a Hall thruster could significantly improve the performance of the mesoscale propulsion systems. The lifetime of an X-40 with improved materials should be 2000-3000 hours, therefore the same cathode lifetime will be required in the cathode environment. The cathode current requirement ranges from 0.1 to 1 A. A field emission cathode can be scaled in size of an emitting area and number of cathodes to provide the required current in a Hall thruster environment. The current density objective is 100 $mA/cm^2$.

The cathode environment of a Hall thruster consists of xenon neutrals and ions. One of the xenon ion populations near the cathode originates from charge-exchange collisions between ions in the thruster ion beam and ambient neutrals. The xenon pressure near the cathode depends on propellant flow rate, thruster performance, and vacuum chamber pressure. During ground testing of an X-40, this pressure should range between $10^{-6}$ and $10^{-5}$ Torr. The charge-exchange collisions produce fast neutrals and slow ions. The slow ions are then accelerated by local electric fields which can direct them towards the cathode. These ions will then bombard the cathode emitting surface after being accelerated through 20 V in addition to the voltage difference between the emitting surface and the gate electrode. The characteristics of these species have not been quantified; however estimates can be made by scaling them from measurements made on larger systems.[10,11] It is estimated that this charge-exchange ion current density will be approximately 2.2 $\mu A/cm^2$ at a thruster discharge current of 0.5 A and local pressure of $2x10^{-5}$ Torr.

### 2.3 Field Emission Electric Propulsion System

Field Emission Electric Propulsion (FEEP) systems also accelerate ions electrostatically to generate thrust; however, unlike the ion and Hall thrusters, the propellant is not ionized by electron bombardment. FEEPs use liquid metal propellant which is fed by capillary forces through a small channel. The channel is often terminated with sharp edges and biased positively with respect to an extraction electrode located downstream of the channel, as shown in Figure 3. The electric field applied between the electrodes deforms the surface of the liquid metal into Taylor cones with cusps. A Taylor cone, at 49.3°, is formed from a liquid metal and circular electrode geometry when electrostatic and surface tension forces are in equilibrium.[12] A cusp forms at the tip causing geometric field enhancement, which further reduces the radius of curvature of the tip, and in turn, further increases the electric field at the tip. When the electric field strength reaches $10^7$ V/cm atoms of metal on the tip are ionized by field ionization or field evaporation. Liquid metal is converted into an ion beam without the transitional vapor phase. Electrons are collected by the column and channel walls and ions are accelerated by the applied electric field through the slit in the extraction and accelerating electrode. The slit width is typically approximately 1 $\mu$m. The gap between the channel and extraction electrode is approximately 1 mm. The applied voltage between the electrodes is typically 9 kV. The thrust can be throttled by adjusting the applied voltage to control the beam energy and ion generation rate.

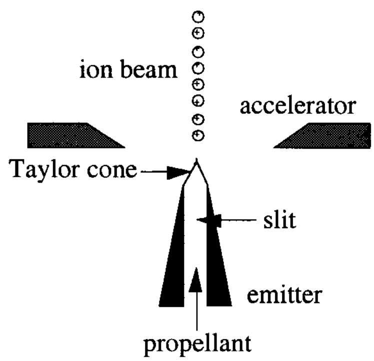


**Figure 3 Field emission electric propulsion system.**

The performance of this system depends on channel slit width, electrode gap, propellant, and applied voltage. Cesium is the preferred propellant because it has a low ionization potential, high atomic mass, effectively wets metal surfaces, and offers compact storage on spacecraft. The orignial FEEPs employed needle emitters, but later evolved into a slit configuration. FEEP systems have demonstrated 100 μN of thrust at 8000 s specific impulse (~80,000 m/s ion velocities) with 9 W of power and a total impulse of 160 Newton-seconds (450 hours at nominal steady state operation). Another system demonstrated 800 μN at 8000 s and 60 W for 60,000 Newton-seconds (20,000 hours at nominal steady-state operation). The thrust level depends on the emitter (extraction) electrode voltage and slit length. A 0.5 cm- slit produces 100 μN with 7.5 kV on the emitter electrode and –3 kV on the acceleration electrode while a 7 cm slit has demonstrated 1.5 mN at the same operating voltages.[13]

Miniaturization of the FEEPs has been achieved with arrays of volcano-shaped ion emitting cones.[14] Arrays of these gated cones have been microfabricated with 1.5 μm cone heights with 1 μm apertures in the cones and 15 μm apertures in the gate electrodes. They have been fabricated with 106 volcano tips/cm$^2$. The advantage of this configuration is that the thrust and specific impulse could be independently controlled by addressing only segments of the arrays. This FEEP configuration will also be more compact and lightweight; therefore they will be more compatible with microscale to picoscale satellites. The disadvantage of this system is the low propellant utilization. A significant portion of the propellant can escape without being ionized. Microscale FEEPs are still under development.

FEEPs require an electron source only for ion beam neutralization to prevent the spacecraft from charging negatively. Hollow, thermionic, and filament cathodes are commonly used with FEEPs. A cesium hollow cathode demonstrated 0.1 mA/W. FE cathodes have demonstrated much higher efficiencies in UHV environments. The FEEP cathode is required to deliver up to several milliamperes in the cesium environment. Both Cs ions and neutrals will interact with the cathode to affect its performance. While it has been demonstrated that cesium improves the performance of FE cathodes, it will reduce emission stability. Experimental and theoretical results have shown that the charge-exchange back-flow current is 1

% of the beam current.[2] With a beam current of 0.9 mA the plasma density was reported to be $2.4\times10^8$. Assuming that the cathode potential will be 20 V below the plasma potential, the charge-exchange current to the cathode region was calculated to be 0.2 mA/cm$^2$, and then scaled with beam current for the estimates shown in Table 1. In this system, the ion energy could be as high as 100 eV.

### 2.4 Colloid Thruster

Colloid thrusters are similar to FEEPs except that charged droplets, instead of single atoms, are field ionized and accelerated.[15,16] An electric field is applied between the capillary tubes feeding the propellant and the extraction electrode to cause separation in the liquid propellant. The propellant is typically doped to increase conductivity. Hydrodynamic instabilities cause the jet to break up into charged droplets. A high and uniform specific charge (coulomb per droplet mass) is optimal to maximize the specific charge efficiency and specific impulse. Electric field strengths, fluid conductivity, and propellant flow rates which are too high create droplet streams with a large distribution of droplet charge-to-mass ratios (low specific charge efficiency). The droplets are either positively or negatively charged depending on the propellant used. A bipolar thruster employs both positively and negatively charged droplets.[15] Operating in this mode, the thruster is self-neutralizing.

The performance of colloid thrusters depends on the propellant, the capillaries, and the applied electric field. Glycerol is the most commonly used propellant. Glycerol doped with sodium iodine produces positively charged droplets. Glycerol doped with sulfuric acid produces negatively charged droplets. Platinum capillaries provide high resistance to corrosion, maximizing lifetime. Bi-polar colloid thrusters were developed with platinum capillaries having 200 μm inner diameters using sodium iodine and sulfuric acid doped glycerol propellants. They produced thrust between 0.2 and 0.5 mN at power levels of about 4.4 W/mN, requiring voltages of 4.4 and -5.8 kV. Specific impulses between 450 and 700 s were estimated. Specific impulses up to 1350 s have also been obtained at 0.55 mN thrust.

Colloid thrusters have not yet been miniaturized, but miniaturization is underway. These thrusters are natural candidates for miniaturization because the high electric fields required for charged droplet emission can be obtained at lower voltages with smaller dimensions. It should be possible to operate these thrusters at milliwatt power levels and integrate them into stacked chip structures for microscale spacecraft.

When a colloid thruster is operated in biploar mode and emits only a positive stream of ions, a charge neutralizer will be required. An electron source must be used which operates at power levels comparable with 4.4 W/mN thruster performance. Filament and hollow cathodes operate at higher powers than this thruster at the required current levels of approximately 0.1 mA. A field emission cathode could easily provide 0.1 mA at much lower power levels, however, the cathode must tolerate the thruster environment. The colloid thruster will generate a fairly hostile environment as colloids may be deposited on the cathode. The pressure in the cathode region and ion flux to the cathode depend on the vacuum chamber pressure and performance of the thruster. This environment has not yet been characterized.

**Table 1 Representative performance and cathode environment of meso- and microscale propulsion systems.**

| | Mesoscale Ion Thruster (5 cm)[17] | Mesoscale Hall Thruster (X-40)[18] | Mesoscale FEEP Thruster [13,2] | Mesoscale Colloid Thruster[19] |
|---|---|---|---|---|
| Thrust (mN) | 2.2-4.7 | 5-32 | 0.001-1 | 0.001-0.025 |
| Power (W) | 50-116[1] | 80-510 | 0.06-60 | 0.3 W (at 25 $\mu$N) |
| Power/Thrust | 23 | 16 | 60 | 12 |
| Specific Impulse (s) | 2300-3100 | 1160-1933 | 8000 (10 kV) | 1000 (5kV) |
| Current (mA) | 230-430(discharge) 44-81(neutralizer) | 500-1700 | 0.006-6 | 0.05 |
| Efficiency | 0.49-0.61 | 0.31-0.55 | 0.98 | 0.75 |
| Thruster Specific Mass (kg/W) | - | - | 0.008 | 1.8 |
| Propellant | Xenon | Xenon | Cesium | formomenite/ Sodium iodine |
| $J_{CEX}$($\mu$A/cm$^2$) | 4000 (discharge)[20] 0.004-0.008 (neutralizer) | 2 -7 | 0.002-2 | - |
| Pressure (Torr) | $10^{-3}$-$10^{-6}$ | $10^{-6}$-$10^{-4}$ | $10^{-6}$ | - |
| Lifetime (hours) | 6000 | 950 (demonstrated), 2000 (possible) | 450-20,000 | 10,000 |

**Table 2 State-of-the-art cathode technologies at low power.**

| | Filament | Thermionic [2] | Hollow[3] | Hollow[21] | Field Emission |
|---|---|---|---|---|---|
| Power (W) | 0.2-10 W/mA | 1.5-2 | **7 W[3]** | 10W/mA | <1 W[4] |
| Current (mA) | - | 1 mA | 100 | - | 120 |
| Propellant | none | none | xenon | cesium | none |
| Dimensions (cm) | | 1 x 1.2 | 1 x 4 | - | 1 x 1 |

**3. Recommended FE cathodes for EP applications**

For FE cathodes to be compatible with electric propulsion systems, they must meet the current density and lifetime requirements in their environments. The fact that they do not require propellant, is a major advantage, however, to compete with conventional cathode technology, they must also consume less than 70 mW/mA through the gate electrode. An efficiency as high as 1 mW/mA will be required to satisfy the power limitations of picosatellites with less than 100 mW total power. The challenge at hand is to provide 10-100 mA/cm$^2$ for 1000-6000 hours with less than 100 V at no more than 1 W/mA consumed by the gate electrode. Ideally, one cathode is developed to satisfy the requirements of all of the systems, therefore, this strategy is employed. The mesoscale thrusters generate the most hostile plasma environments because of their densities, therefore cathodes will be developed and tested in these environments first. Future results may necessitate the relaxation of the requirements of each of the EP systems.

[1] Thruster has been operated as high as 300 W sucessfully.
[2] Made by AEG Elektrische Rohren GmbH
[3] Consumed by keeper electrode.
[4] Into gate electrode.

The FE cathode technology which has demonstrated the highest current density, lowest operating voltages, and highest efficiency to-date is the Spindt-type field emission array cathode. It is also the most mature and accessible of the microfabricated FE cathodes. Less mature FE cathode technologies include thin Negative Electron Affinity (NEA) films and carbon nanotubes. Rigid carbon nanotube cathodes have not yet been grown in microfabricated gate structures, therefore the operating voltages have been greater than 100 V. Carbon and diamond NEA films have demonstrated turn-on electric fields which are lower than the Spindt-type cathodes and 100 mA/cm$^2$, however, either their operating voltages are too high or their efficiencies are much lower than 1 mW/mA.[22,23,24] **Spindt-type cathodes have demonstrated current densities greater than 2000 A/cm$^2$ from Mo[25,26] FEA cathodes and 2 A/cm$^2$ from Si FEA cathodes[27] in Ultra High Vacuum (UHV) in triode configurations with efficiencies higher than 100 mA/mW.[2]**

At this time it is believed that to meet the current density and lifetime requirements the Spindt-type cathodes should be coupled with carbide or NEA material films. Experiments have shown that xenon will not affect the cathode work function.[24] It has also been shown that the energy threshold for sputtering Mo and Si FEA cathodes with xenon ions is 39 eV and 48 eV, respectively.[24] Cathode operating voltages will then be limited to approximately 43 V (Mo) and 52 V (Si) to achieve lifetimes greater than 6000 hours in a neutral xenon environment where only one ion population is considered. In the thruster environment, the charge-exchange ion population will further limit the operating voltages to approximately 19 V (Mo) and 28 V (Si) because ions will be accelerated through approximately 20 V before entering the gate electrode apertures. With optimistic FEA cathode characteristics including gate aperture radii of 0.2 μm, excellent uniformity, effective tip radii of 4 nm,[28] and packing densities of 5x10$^7$ tips/cm$^2$, modeling results show that it is impossible to attain 100 mA/cm$^2$ at these operating voltages with Mo and Si FEA cathodes operating in the plasma environment generated by a Hall or ion thruster.[24] Other limitations include a lower limit on cathode gate electrode thickness because of potential delamination due to excessive heating from electron current and ion bombardment in a plasma environment. The performance can be improved by coating the cathodes with a lower work function material. If the coating decreases the sputter yield also, higher operating voltages will be tolerated while meeting the lifetime requirements. Materials with these potential properties include HfC,[29] ZrC,[30] and carbon/diamond films.[31] Mo and Si FEA cathodes have been successfully coated with carbide, carbon, and diamond films.[32,33,34,35,36] These films have significantly improved the cathode performance in current and stability in UHV and in more hostile environments. Depending on the performance of the FEA cathodes with the thin film coatings, the cathode performance with these films may still not meet both the current density and lifetime requirements

Further cathode ruggedization is recommended with an electrostatic ion filter and an arc protection architecture. A Cathode Lens and Ion Repeller (CLAIR) should be used to repel the charge-exchange ions before they bombard the microtips.[24] CLAIR consists of 3 microfabricated electrodes in addition to the gate electrode. This electrode configuration resembles a einzel lens. It focuses the electron beamlets through the electrodes and retards the charge-exchange ion flux. Using CLAIR will increase the tolerable operating voltages by more than 20 V and the current by several orders of magnitude while satisfying the lifetime limited by the ion bombardment. Currently CLAIR is a concept which has only been theoretically evaluated using PIC codes. Fabrication of this device is underway.

Premature cathode failure should also be controlled with a current limiting architecture. In the hostile thruster environments the cathodes will get contaminated by cathode, thruster, and facility materials. Often this contamination results in excessively high current densities and an arc between the tips and the gate electrode. Several architectures have been recommended to limit the current through a tip to quench the current before an arc. The most favorable current limiting option is the VECTL architecture[37] because it is a passive configuration which is microfabricated into the silicon substrate below the microtips. Packing densities of $5x10^7$ tips/cm$^2$ have been achieved with this architecture. High-resistivity wafers reduce the cathode efficiency and only protect the cathodes on start-up. Field effect transistor configurations are another current limiting configuration; however, they can significantly reduce the packing density of the arrays of microtips.

## 4. Conclusions

Considering all of the challenges in integrating FE cathodes and EP systems discussed, the FE cathodes required will have to incorporate the best cathodes technology available and design improvements which have not yet been developed and proven. Advances in FE cathodes technology may introduce a cathodes which is much simpler than the configuration recommended in this article. For now the cathode design includes gate aperture radii ~0.2 um, packing densities of $5x10^7$ tips/cm$^2$, effective tip radii of 4 nm, with HfC, ZrC, or C films on Si or Mo arrays to achieve 100 mA/cm for more than 6000 hours in EP systems environments. CLAIR structures are recommended with VECTL architectures to meet the performance requirements. While a cathode with all of these features integrated is possibly several years from being available, these advanced features are being developed and tested individually in the environments of interest. Advances in FE cathodes technology will be incorporated into the cathode design as they develop.

## 5. Acknowledgements

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