Development of Field Emitter Array Technology for ED Tether Propulsion*†

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Field Emitter Arrays (FEAs) are being developed for electron emission in electrodynamic tether applications. Instead of a single hot (i.e. high powered) emitter or a gas dependant plasma contactor, FEA systems consist of many (up to millions per square centimeter) of small (micron-level) cathode/gate pairs on a semiconductor wafer that effect cold emission at a relatively low voltage. Each individual cathode emits only micro-amp level currents, but a functional array is capable of multiple amp levels. This potentially provides a low power, relatively inexpensive technique for the amp level current emissions required for electrodynamic tether propulsion systems. Critical issues in the development of FEA systems which are discussed here are survivability in ionospheric and spacecraft environments, emission efficiency (i.e. power required to overcome space charge limits in the ionosphere), and electrical integration requirements. Tests of FEA devices are being conducted at the University of Michigan to evaluate their performance and results to date from these tests will be presented here.

Nomenclature

ED: electrodynamic
FEA: field emitter array
Vgt: gate tip voltage
ε_0: permittivity of free space
e: electron charge [C]
m_e: electron mass [kg]
T_o: electron emission energy [eV]
D: gap spacing [m]
V: gap voltage [V], or spacecraft bias w.r.t. plasma
W: emitter width
r_b: emitter radius
A: emitter area [m^2]
s: sheath size [m]
$J_{CL}(N)$: N dimensional Child-Langmuir limit [A/m^2]

Introduction

Space electrodynamic (ED) tethers offer the opportunity for in-space “propellantless” propulsion and power generation around planets with a magnetic field and an ionosphere (e.g., Earth and Jupiter). In general, moving a conductor across a magnetic field generates an electromotive force (EMF) to drive current through the conductor if a means to “close the circuit” is available. For example, using gravity gradient stabilized space tethers around Earth it is possible to have kilometer-scale structures that move across the geomagnetic field at rapid velocities, generating 50–250 V/km EMF in an eastward-moving system at a mid- to low-latitude orbit inclination. Current flow through the tether is enabled by collecting electrons from the ionosphere at or along one end of the tether and, either injecting electrons back into the ionosphere or

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collecting ions at the opposite end. For an orbit lowering application, energy for collecting electrons, driving currents, and electron emission can come directly from the tether kinetic energy. For orbit raising thrust it must come from solar cells or other onboard energy sources. In either case, electron injection is necessary to achieve the highest possible efficiency given the low mobility of ions. The focus of this paper is electron injection via FEA systems.

Space FEA Systems

Figure 1 shows a single FEA tip. The scale is sub micrometer.

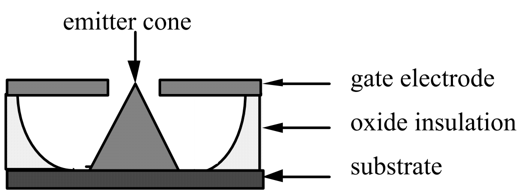


Figure 1- Diagram of a single element of an FEA

A typical array is manufactured on a semiconductor wafer with up to millions of individual tips per square centimeter. Typical gate-to-tip operating voltages are in the range of 50-100 V, and typical currents can be on the order of 1μA per tip.

The advantages of FEA systems over alternative electron emission devices are a lack of need for consumables and moderate power requirements. Hollow cathode plasma contactors (HCPCs), which operate by generating a dense plasma plume and injecting electrons into the ambient plasma across a double layer sheath, use a consumable gas supply and require heater power, but may need the least drive power to inject electrons into the plasma. Electron guns require higher injection voltages and power than FEAs and HCPCs and are sensitive to pressure gradients (but are capable of the most dense electron beam generation at the highest injection current levels).

There are several issues facing FEA systems in space applications. An FEA emits charge with an initial velocity depending on the gate-tip voltage, and the voltage of any other associated acceleration or protection grids. As charge leaves the cathode into free space, or a plasma, each charge emitted experiences a field created by the charges before it. If the emission density is too high, this effect will decelerate the charge and, in the limit, reverse the flow and reflect current back on the emitter (so called space charge limited emission (Luginsland, 1996)). This space charge limitation is an important consideration for FEA and other charge emission systems. The implications of this limitation in relation to ED tether propulsion and techniques for mitigating it are being studied at the University of Michigan (Gilchrist, 2000) and elsewhere (Marrese, 2000). An overview of this issue is presented here, as well as analysis of the tradeoffs between different electrical configurations of an FEA system in relationship to space charge limits and overall emission efficiency.

Another issue for FEA systems is the effect of contamination. In order to achieve electron emission at low voltages, FEA systems are built on a micron level scale size. They are also dependent on having a low work function surface. This can render the device extremely sensitive to contamination, especially by hydrocarbons and other large easily polymerized molecules (Spindt, 2001). The ambient environment at the surface of a spacecraft is far from ultra-high vacuum, especially soon after launch. Ionospheric contaminants may be a problem (atomic oxygen in particular has been identified as an issue), and more significantly outgassed spacecraft fuels, lubricants, etc. can contaminate the FEA causing shorts or other forms of failure. Techniques for avoiding, eliminating, or operating in the presence of contaminations are therefore also critical. Initial testing at the University of Michigan has to date focused primarily on this issue.

First, we begin with the theoretical review of electron charge emission. Then, we discuss more practical experimental issues.

Electron Emission and Spacecharge Effects

The cold cathode emission, or field emission, used in FEAs is a phenomenon which occurs whenever the electric field at the surface of a material (typically a good conductor so that the charge removed is easily replaced) is sufficient to enable electrons in the conduction band to overcome the work function of that material and escape. This typically requires electric fields on the order of hundreds to thousands of volts per meter, or higher, which is achieved in FEAs with only tens of volts applied externally thanks to the small dimensions involved. For example, 5 volts applied across a one micron gate-tip gap provides 5 million volts per meter field strength.

The electrons pulled free of the tip material are accelerated towards the gate by the same electric field that pulled them free. Electrons leaving the FEA have a kinetic energy corresponding to the voltage that they were accelerated through. In a device operating at 50V, this velocity would be about 4 million meters per second. Thus for individual electrons, an FEA accomplishes it's goal of moving charge away from the spacecraft very effectively.

The problem arises when the level of current (number of electrons) emitted reaches sufficiently high levels. Each electron creates a field around it, as would any charged body. Each emitted electron "sees" the combined effect of the electrons emitted before it. Being like charges, the electrons repel, and subsequently emitted electrons are decelerated by the previously emitted electrons. Eventually the combined effect of these fields can become sufficient to halt the electron's motion and reverse the flow back to the emitter and spacecraft. This general effect is called the space charge limit, and was first discussed by Child and Langmuir who formulated the Child-Langmuir law for space charge limited flow. In one dimension this is as follows [Luginsland, 1998]:

$$I_{CL}(1) = \frac{4\varepsilon_o}{9e}\sqrt{\frac{2}{m_e}}\frac{T_o^{3/2}}{D^2}\left[1+\sqrt{1+\frac{eV}{T_o}}\right]^3 A \qquad (1)$$

where the condition that the initial velocity is not assumed to be zero has been allowed. When the space charge limited flow condition is reached, a portion of the emitted current returns to the spacecraft. In an electrodynamic tether propulsion mission, this means that the thrust capability of the system is limited because the amount of current which can be flowed through the tether is limited. The flow for a given voltage and given current across a given gap (one-dimensional approximation as calculated above) will take on a time domain response as shown in Figure 2, created in XPDP1 (Verboncoeur et al., 1993).

Electrons bunch up and are reflected until the reflected current is collected, the bunch dissipates, and more electrons can escape until the process repeats.

Figure 2- Time domain current when emission exceeds the space charge limit for a 1D case

As Equation 1 indicates, the current level of the space charge limit (the maximum current which can be emitted) increases with the initial energy of the electrons. An FEA operating at 60V will have a higher space charge limit than an FEA operating at 50V. Furthermore, the current limit decreases as the distance over which the electrons must be emitted increases. In this case it is assumed that the relevant distance is the width of the sheath around the spacecraft (any spacecraft in the ionosphere will have a sheath region, an area depleted of electrons and ions, surrounding it). This sheath increases in size with the voltage difference between the spacecraft and the plasma, causing the space charge current limit to decrease. (The detrimental effect of having to traverse a greater distance is stronger than the beneficial effect of a greater bias on the other side of the gap that the electrons are striving for.) The relationship between the size of the sheath and the potential of the spacecraft for small sheaths is as follows (Lieberman & Lichtenberg, 1994):

$$s = \left(\frac{2\varepsilon_0 V}{en_s}\right)^{1/2} \qquad (2)$$

This works out to 1.5cm for a spacecraft at -1V relative to a $5x10^5/cm^3$ plasma, and this is the value we use for the gap spacing D in our equations below. Once the electrons cross the sheath, the space charge situation improves as they can be more easily accommodated by the surrounding plasma by electrons and ions moving to balance the emitted charge and reduce the resultant electric fields. The best situation is to keep the spacecraft potential low and therefore the sheath small. In the low earth orbit environment the typical spacecraft floating potential (unaffected by tethers) is about –1 V. The goal of FEA charge control is to keep the spacecraft as near this potential as possible despite the current being driven through the tether.

In the most simple one dimensional analysis, for a $1cm^2$ emission area, a -1V spacecraft bias, and 50 eV emission, the space charge current limit is 3mA (based on Equation 1). This is an effective lower limit to the ability of an FEA to emit charge (assuming that crossing the sheath is the primary limitation). So to get 1 A of emission would require a minimum of just over $300cm^2$ of emitting area. This is possible, but higher current densities would be ideal for most applications. No accommodation need be made in this analysis for space charge limits increasing as the emitter area increases, because the 1-D analysis already assumes the worst case situation- an infinite sheet of charge.

More advanced analysis indicates that significant improvement can be attained when you consider spreading of the emitted electrons in multiple dimensions. Luginsland [1996] suggests that the improvement by going to a long, thin emitter (modeled as an infinite strip) would be a factor of 2, via Equation 3 which was derived via numerical analysis of computer simulation results. (Using a 0.5 cm wide emitter, which gives a W/D of about 1/3 for our 1.5cm sheath.)

$$\frac{J_{cl}(2)}{J_{cl}(1)} = 1 + \frac{0.3145}{W/D} - \frac{0.0004}{(W/D)^2} \quad (3)$$

This would reduce the required area to 150 cm^2 for 1 amp at 50 V gate-tip.

Similar improvement is obtained by considering three dimensional spreading. A theoretical calculation by Humphries [1990] suggests an improvement of 2.5 for a $1cm^2$ (r_b=.564cm), 1.5 cm sheath case, as per the following equation.

$$\frac{J_{CL}(3)}{J_{CL}(1)} = \frac{\left[r_b^2 + (D/2)^2\right]}{r_b^2} = \left[1 + (D/2r_b)^2\right] \quad (4)$$

This equation is for a flat circular emitter. If the emitter's radius is large there is little improvement over the 1-D infinite plane case. Considering the third dimension does not effect the calculation very much for non-miniscule emitters constrained to a flat spacecraft body. More complicated analysis is required to showcase the potential of a fully three dimensional FEA solution. For example, a hemispherical emitter extending out from the surface of a spacecraft should have a significantly higher emission capability, which is not shown by Equation 4.

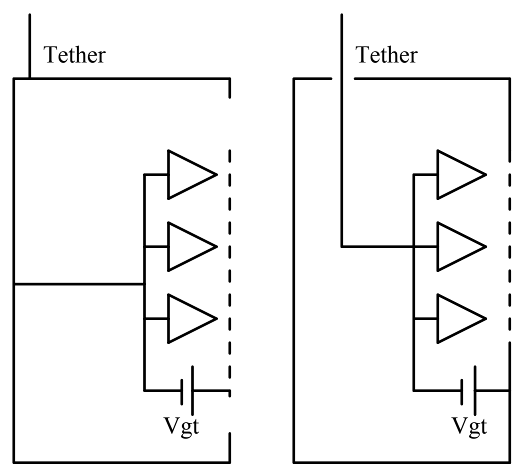
If higher current levels are required, additional techniques can be implemented to improve the space charge limit. Natural three dimensional spreading can be guaranteed and improved upon by installing electron optics (in the form of biased curved grids or rings) to spread the beam at the emitter. Development of this and other techniques is also under way at the University of Michigan.

The space charge emission limits are further effected by the electrical integration of the FEA with the spacecraft, as discussed below.

FEA Electrical Configuration

Decisions must be made as to how to connect the FEA (gate and tips) to the spacecraft. How the gate and tip are biased relative to the spacecraft result in various advantages and disadvantages to the system overall.

The figures below illustrate the two basic configurations.



Basic Grounded Tip Configuration

Basic Grounded Gate Configuration

Figure 3- Two possible electrical interfaces between an FEA and a spacecraft. Each has it's own advantages and disadvantages.

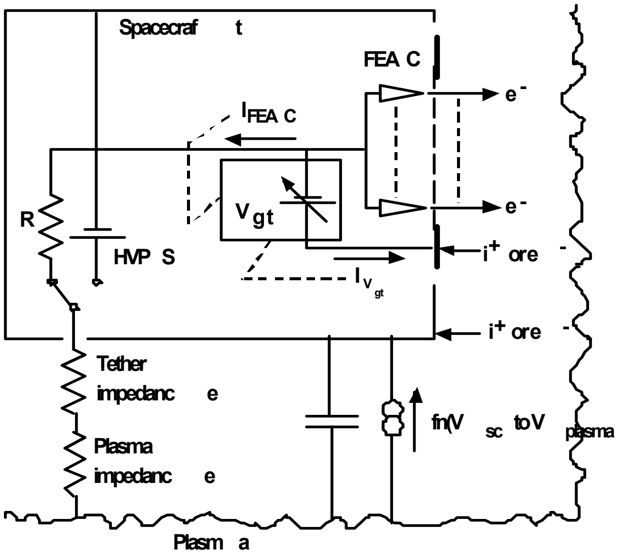


Figure 4- More complete circuit model of the grounded tip configuration.

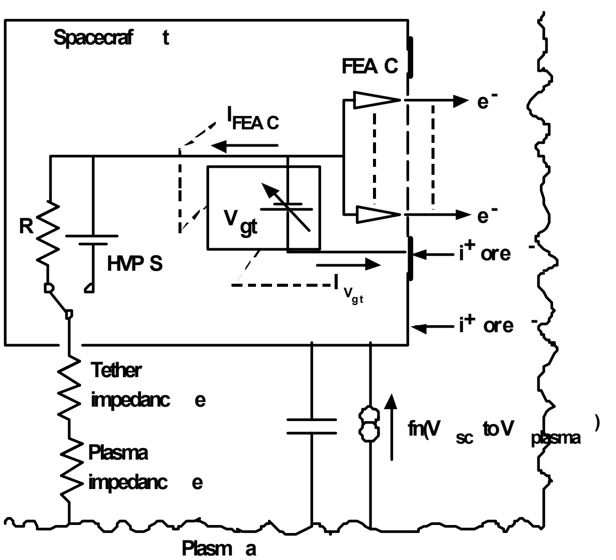


Figure 5- More complete circuit model of the grounded gate configuration

A factor in this decision is that the spacecraft potential (driven by the current collected by the tether) may vary widely on the electron emitting end and can reach hundreds of volts negative. As the FEA operates it can bring the spacecraft up to neutral bias and even above, if the FEA's current provision capability exceeds the tether and/or opposite tether end current collection capability. Therefore, care must be exercised in how the tip is biased relative to the gate and spacecraft. If the tip is connected directly to the tether, as in the first diagram of the grounded gate configuration, a sudden swing in the voltage at the tether (caused, perhaps, by changing ionospheric conditions) could put a sudden heavy load on the gate-tip voltage supply.

Advantages of the grounded tip configuration include stability for the gate-tip supply (less effect by tether voltage swings) and low return current from collected ions and electrons (because only collection at the gate surface effects the supply, not the entire spacecraft). One disadvantage is that the emitted electrons must move away from a gate biased positive relative to the plasma (assuming the spacecraft is close to the plasma potential) and this will act as a decelerating force, increasing space charge limitations.

The advantage of grounded gate is that electrons leave through a gate held at the same potential as the spacecraft, no decelerating fields will exist (or if the spacecraft is biased negative, a beneficial accelerating field will be present). One major disadvantage is that the gate-tip voltage can be directly effected by swings in the tether voltage. This becomes an especially significant concern when the tether is connected and disconnected for mission propulsion reasons- potentially resulting in several hundred volt spikes that the gate tip power supply must suppress to avoid shorts in the entire array.

Experiments done in the University of Michigan Cathode Test Facility (CTF) demonstrated the distinct difference between the two techniques. The following plot shows the amount of current returning to the gate in the grounded tip and grounded gate configurations as the gate tip bias is increased. As expected, in the grounded tip configuration a far greater number of electrons are unable to escape (are re-collected by the gate). This particular data was gathered with a 150 V anode bias. At higher biases, the effect is less pronounced (the experimental setup is covered later).

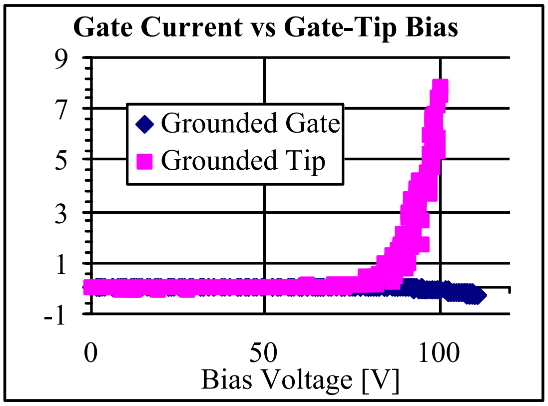


Figure 6- Gate current versus gate-tip bias for grounded gate and grounded tip configurations

Combinations of these techniques are possible as shown in Figure 7. One advantage of a multiple gate configuration is that the second gate could be shaped to defocus the emitted electron beam, further mitigating space charge effects by spreading the electrons apart (as discussed above).

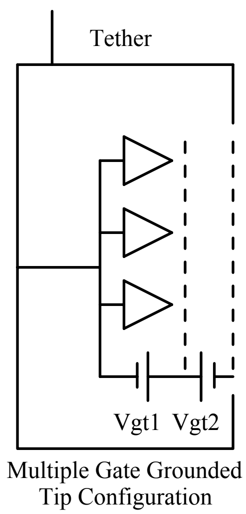


Figure 7- Multiple gate configuration with grounded tips.

The experiments at the University of Michigan have mostly been conducted in the grounded gate configuration. The decision of which configuration to use on a flight mission will have to be made considering all aspects of the mission- balancing cost and equipment space/weight availability versus power availability and other tradeoffs.

Experimental evaluation of these various configurations are underway as covered in the next section.

Testing at The University of Michigan

FEA tests have been performed in the Cathode Test Facility (CTF) at the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan.

The goal of these tests is to demonstrate the feasibility of FEA operation in the earth's ionosphere, and to work out issues related to that operation. Testing of FEA devices in pure vacuum has been done by the manufacturer and others. Testing in neutral gas environments has been done by Marrese at JPL (Marrese 2000). The primary advantage of the CTF setup at the University of Michigan is the size of the chamber, and therefore the ability to create plasma environments with sufficiently distant wall/edge effects to accurately simulate the electron/ion interaction with FEA emission.

The original plan was to calibrate/baseline the test setup with a verification of the operation of an FEA device in pure vacuum, followed by neutral gas tests (also to provide a baseline reference), and then to focus on operation while exposed to a plasma. The plasma (probably Xenon) would be generated with a hollow cathode plasma contactor. Testing would be done first with an anode to collect emitted electrons, and then progressing to the anode located further and further away from the FEA and eventually removed entirely, demonstrating the full ability of FEA to dissipate charge into a plasma. The setup (described below) is capable of emulating a variety of spacecraft biases relative to the plasma as well as a variety of plasma densities and constituents.

Unfortunately, while basic operation has been verified, a number of problems have been encountered relating to possible contamination in the chamber, and it has not yet been possible to accomplish tests with neutral gases and plasmas. In response, the initial test setup has been modified to include a filament to clean the FEA via heating and electron bombardment. The next section details the results of tests so far.

Experimental Setup

FEA tests are run in a vacuum chamber called the CTF. The CTF is a two meter long by 60 centimeter diameter chamber that is pumped by a 135 CFM mechanical pump for roughing and a CVI TM500 (20 inch) cryopump with a measured xenon pumping speed of 1,500 l/s. Base pressure for the facility is 2 x 10^{-8} Torr. The facility consists largely of components either granted to PEPL by NASA Lewis Research Center or bought with funds from NASA Lewis Research Center and the Jet Propulsion Laboratory.

Test Setup

The following diagram shows the schematic concept for FEA tests in the CTF.

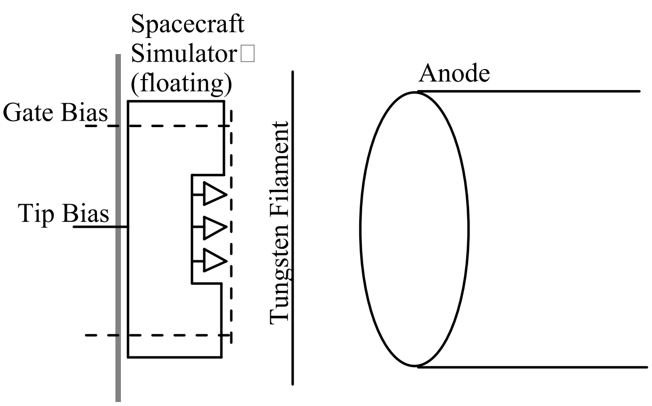


Figure 8- Overview of CTF test setup

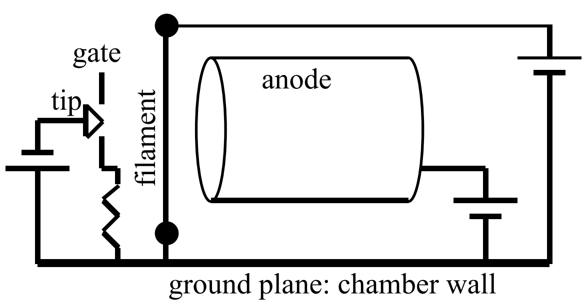


Figure 9- Electrical schematic of the test setup- note the grounded gate configuration.

Gate current is measured with a Keithley 486 picoammeter, tip current and voltage is controlled and measured with a Keithley 2400 source meter, and anode current is measured with a Keithley 2000 multimeter. Data from these devices are recorded to computer via custom LabViews software. Excessive gate currents are prevented with a 5 M-ohm resistor in the gate to ground path. Gate-tip bias is controlled via LabViews through the 2400 source meter. Anode bias is set with a manually controlled power supply (Sorenson 600-1.7 or Kepco BOP 500M). A neutral gas feed system is attached to the chamber, capable of Nitrogen and Oxygen, and soon also water vapor. A Kurt Leskor AccuQuad RGA is attached to the chamber, capable of partial pressure analysis down to 10^{-13} of constituents up to 200 AMU.

For tests run with the filament in place, an HP 6032A 50A GPIB controlled power supply is used to run up to 30 amps of current through the thoriated tungsten. A Keithley 2000 multimeter is used to measure the bias of the filaments. The Keithley 2400 again is used to bias the externally shorted gate and tip, and measure the current being collected. (Electron bombardment is done with the gate and tip shorted to prevent high currents from damaging the gate film.) The 2400 is controlled via LabViews. Bombardment at voltages higher than the 210V maximum voltage of the 2400 is achieved by biasing the filaments (and the entire 6032A) negative.

Test Results and Contamination Issues

Initial testing of FEA devices in the CTF met with severe challenges. Devices were unable to emit despite high gate-tip voltages. Several devices shorted out destructively without generating any emission. Others emitted some, but only sporadically. It is believed that the problem is hydrocarbon and/or silicon grease contamination from the roughing pump and chamber seals respectively.

In response to this, the chamber was cleaned, a foreline oil trap was installed in the roughing pump connection line, and the test setup was simplified (to remove sources of contamination in the setup itself). These steps were apparently insufficient.

One FEA, 1100F, was successfully run in the CTF for a period of several weeks. Initial emission was sporadic (see figure), but over time stabilized to a consistent output. Once the device began emitting continually, contamination was apparently no longer an issue (as long as emission continued).

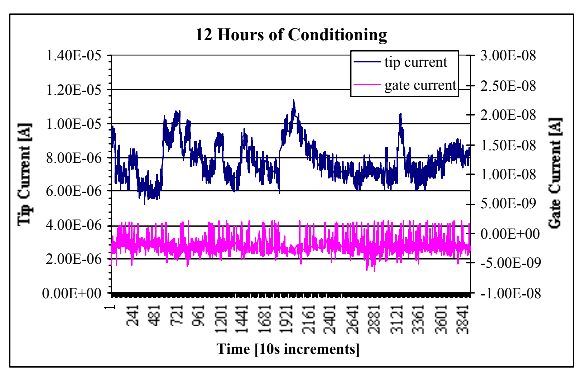


Figure 10- Early emission of an FEA in the CTF

Characterization of this device in vacuum was consistent with manufacturer specs. (Figure 11) However, once the chamber and FEA were shut down for two weeks, we were unable to re-initiate emission, implying that contamination was a continuing process rather than a by product of the initial roughing down of the chamber or installation.

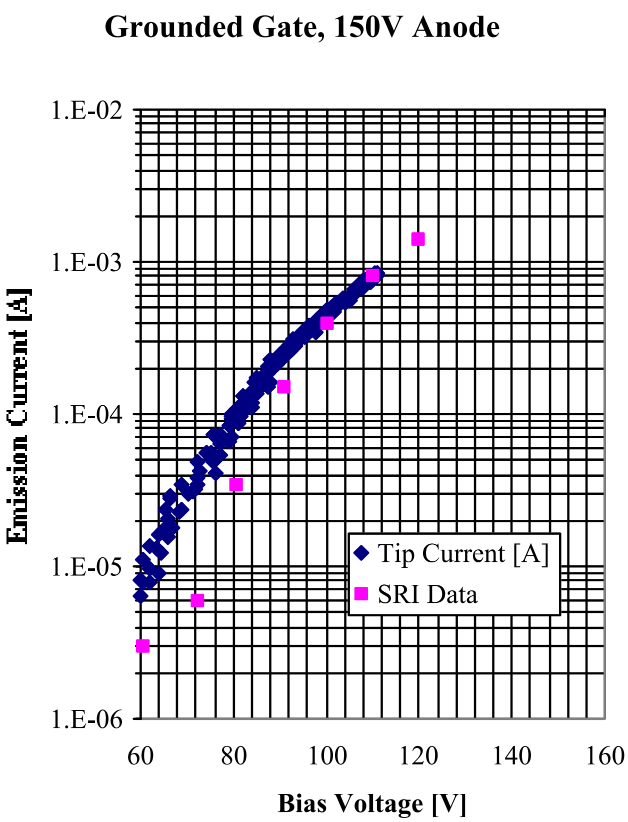


Figure 11- Fowler-Nordheim plot of emission of FEA 1100F after tens of hours of operation. Experimental data compares favorably with manufacturer specs.

Chemical Analysis

A contamination analysis was performed in the Cathode Test Facility using special aluminum test coupons provided by Mark Anderson at JPL (Colleen Marrese-Reading helped initiate and fund this effort). The purpose of these tests were to help determine if the chamber and specifically the pumpdown process could be a source of important contamination. The test coupons were exposed to the pumpdown process as listed below, and then shipped to JPL for analysis. The test configurations are summarized in Table 1 while results are given in Table 2.

The following results were determined in the analysis of the test coupons at JPL:

The plates (4,5) exposed to the roughing and cryopump process collected about a monolayer level (~.1 ug/cm^2) of aliphatic hydrocarbon (AHC) and silicone (polydimethylsiloxane). The plates exposed to the roughing process only (1,2) had only a trace of similar residue. The blank (3) was relatively clean.

There are many potential sources for both AHC and silicones including pump oils, lubricants, adhesives and polymer materials.

Table 1- Test Coupon Locations

#	Sample Position/Exposure
1	Same orientation and location as FEA. (facing the cryopump, end of chamber) Exposed to roughdown only (4 hours in chamber).
2	90˚ orientation (facing upwards), mid-chamber. Exposed to roughdown only (4 hours in chamber).
3	Outside the chamber exposed to lab atmosphere
4	Same orientation and location as FEA. (facing the cryopump, end of chamber) Exposed to roughdown and cryopump to 1e-7 (36 hours in chamber).
5	90˚ orientation (facing upwards), mid-chamber. Exposed to roughdown and cryopump to 1e-7 (36 hours in chamber).

Table 2- Contamination Analysis by Coupon

Sample	**Chemical Functional Group**	**Total Amount ug/cm^2**
Sample #3 Blank Plate	AHC(75%), Ester (25%)	~0.008
Sample #1	AHC(91%), Ester (3%), Silicone(6%)	0.03
Sample #2	AHC(75%), Ester(2%), Silicone (33%)	0.03
Sample #4	AHC(57%), Ester(3%), Silicone (40%)	0.09
Sample #5	AHC(50%), Ester(3%), Silicone (47%)	0.09

The RGA attached to the chamber shows sporadic indications of MP oil. Primary constituents with the chamber at near base-pressures are water vapor and nitrogen, as expected, but also with an indication of 0-18% or higher MP oil, varying greatly with each subsequent scan. It is as yet uncertain whether this indicates a limitation of the RGA or a fluctuating or sporadic oil contamination level.

The present assessment of the contamination studies to date is that some hydrocarbons are present, on the order of a monolayer per day. The amount of contamination appears to be a function of time. The question of whether the contamination amount would continue to increase with time will require additional tests. For the size of the CTF chamber, these results are actually very good. Whether a monolayer is adequate to significantly degrade performance is under evaluation. Developing the ability to operate FEA devices under these conditions is now one of the primary goals of this research.

The first implemented response was to attempt cleaning of the devices.

Cleaning Techniques

If surface contamination is preventing emission, it may be possible to remove that contamination before biasing the FEA. To this end, a cleaning technique was developed consisting of placing a thoriated tungsten filament between the anode and the FEA. This filament allows both heating and electron bombardment of the FEA.

FEA 1136B was loaded in the chamber into to the new spacecraft simulator setup. An initial test was run biasing the device up to 50V while testing for emission. No emission was detected. Relatively high levels of gate bleed current were observed. This is consistent with initial tests of previous devices, indicating that the contamination problem is still present.

Subsequent heating in stages up to 200˚C and bombardment up to 25uA and several hundred volts were ineffective. In many cases the gate bleed (i.e. gate/tip short) was worse after heating/bombardment than before. The following figure shows the setup in operation.

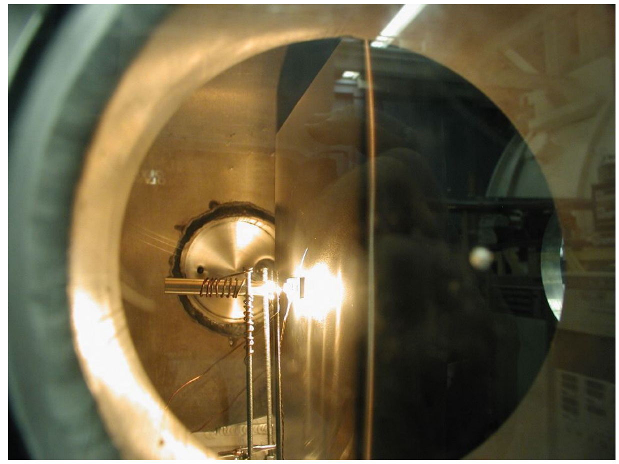


Figure 12- FEA system undergoing cleaning at 88˚C and 1uA bombardment current at 100V.

It may be that higher temperatures (the filaments were unable to sustain current high enough to go above 200˚C) would be more effective, or that higher bombardment currents or electron energies would have some effect. Additional testing in the future may be directed at these questions.

An alternative solution to cleaning is the prevention of contamination via covering the FEA prior to emission. This solution was pursued in parallel with the above cleaning techniques.

Small Vacuum Protective Enclosure

If contamination from the chamber- most likely desorbed oils and greases- coat the FEA over time, one solution is to cover the FEA in a small ultra-clean containment unit until emission is initiated. (The pumpdown time of the chamber to a vacuum of high 10^{-8} Torr is approximately 12 hours.)

Design is nearly complete at the University of Michigan of a new Small Vacuum Protective Enclosure (SVPE). The purpose of this container would be to provide an ultra clean environment for protection of the FEA from chamber contaminants during pumpdown between experiments. Given the experiences in this chamber, and the nature of FEAs in general, such a device will almost certainly be required for flight applications as well since the level of contamination surrounding a spacecraft on the ground and immediately after launch (during initial spacecraft outgassing) is thought to be high.

The system will use a single drive motor attached to a threaded rod to lift and rotate the protective cover out of the way. The cover will use a greaseless vacuum seal to attach to the underlying base plate. The figure below shows the design.

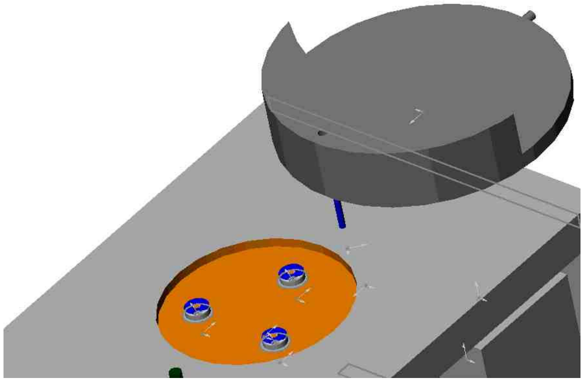


Figure 13- CAD drawing of the SVPE.

In CTF tests the device will protect the FEA(s) from exposure to chamber contaminants before emission testing is begun. After testing, it will contain the FEA(s) in vacuum (by rotating and lowering the cover back into place) until testing is resumed, even if the SVPE is removed from the chamber.

In flight applications, an equivalent of the SVPE would protect the FEA from contamination during integration and testing on the ground, during launch, and for the time on orbit until FEA operations commenced. For shuttle missions or other recoverable experiments/applications, it can protect the devices for re-use and uncontaminated post-mission study on the ground.

Fabrication of the SVPE, or prototypes thereof, is planned for Fall 2001.

Conclusion

FEA spacecraft charge control systems will be a valuable enabling technology for a variety of space applications. The theoretical concepts have been proven out, and development of conclusive ground tests is underway. There are issues that remain, particularly in the area of contamination sensitivity and control, but solutions are under development that show a high probability of success.

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