Operating Characteristics of a Re-generable Field Emission Cathode for Low-power Electric Propulsion

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This research investigates the discharge characteristics of a field-emission cathode for use in Electric Propulsion (EP) that has the ability to be re-generated when the emitter tip becomes damaged. Emitter tip re-generation is possible by using Taylor cone formation from an operating liquid-metal ion source (LMIS) in an effort to solidify, or quench, the ion emitting cone to preserve the sharp protrusion so that it can then be used for electron emission. Multiple electron emission I-V curves were taken after tips were formed by quenching the LMIS at ion discharge currents ranging from 1 to 25 μA. Fowler-Nordheim modeling was then used to estimate the emitter tip radii of each quenched emitter and showed that emitter tip radii decreased from about 45 nm from a tip quenched at 2 μA down to about 15 nm when quenched at 25 μA. Also, a 46 hour test was done using a single emitter that was quenched at 15 μA. Electron I-V curves were taken at the start, middle, and end of the test that showed no degradation in tip performance.

Nomenclature

a = Fowler-Nordheim term (see Equation 2)
b' = Fowler-Nordheim term (see Equation 3)
E = local electric field (V/m)
I = discharge current (I)
k = empirical relation relating tip radius and gap spacing
V = extraction voltage (V)
V_{max} = extraction voltage required for 0.5 μA of emission current
r = emitter tip radius (m)
α = Nordheim image-correction term
ϕ = work function (eV)
μ = Fowler-Nordheim term

I. Introduction

INTEREST in the miniaturization of space propulsion has been growing over the past 10 to 15 years. Missions such as the DARWIN space interferometer and LISA pathfinder showed a need for a thruster capable of producing 0.1 to 1000 μN of thrust with low thrust noise and high thrust precision. An ideal candidate that could meet those needs was the field emission electric propulsion (FEEP) thruster.[1, 2] FEEP thrusters are unique in that they don't require a neutralizer for propellant ionization. However, a cathode is still necessary to maintain spacecraft neutrality since an operating FEEP thruster causes a small space charge to build up. Since these thrusters operate using only a few Watts of power and are propellant-less, traditional neutralizers cannot be used due to their relatively massive propellant and power requirements. Most traditional neutralizers, such as hollow cathodes, require propellant and 100's of Watts of power to thermionically emit electrons.[3] Therefore, a propellant-less and low-power neutralizer is necessary. The ideal candidate was the field emission cathode. These cathodes use nano-scale sharpened electrodes with locally enhanced electric fields to stimulate electrons to tunnel out of the electrode via Fowler-Nordheim emission. Since the local electric field is inversely proportional to the electrode tip radius, the sharper the emitter tip, the lower the electric potential needed to obtain electron field emission.[4]

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The motivation for the research reported here is the limited lifetime of current micro-fabricated field emitters. As electron discharge is continued for long durations, the emitter tip begins to wear and blunt. When the sharpness of the emitter tip decreases, the local electric field decreases. This circumstance is unfavorable and eventually renders the emitter tip useless as an electron source. Where current field emitters would be destroyed at this point, the process described here allows for the re-generation of a sharp tip. The re-generation can be repeated an (almost) unlimited number of times, providing a mechanism for an extremely long-life field-emission neutralizer.

In 2007, Makela and King proposed and demonstrated a technique for re-generating emitter tips using a liquid-metal ion source (LMIS) to construct nano-scale metal structures intended for use as electron field-emission neutralizers for space applications.[5] Historically, LMIS have found extensive use as ion sources of high brightness in focused ion beam materials processing applications[6] and, more recently, as EP thrusters via the FEEP technology mentioned previously.[7-9] In an LMIS or FEEP thruster, an intense electric field is created near the surface of a low melting-temperature liquid metal, such as In, by a downstream electrode. A balance between the liquid surface tension and electrostatic forces cause a structure known as a Taylor cone to form in the liquid as shown in Figure 1.[10] Because the Taylor cone has a very sharp tip, geometric enhancement of the local electric field at the cone tip is sufficient to extract metal ions directly from the liquid. The ions emerge from a very narrow (few nanometer diameter) liquid jet at the cone apex and are subsequently accelerated by the electric field to either produce thrust (FEEP) or for materials processing applications (LMIS). Other applications and areas of interest for the use of focused ion beams include lithography, semiconductor doping, sample preparation for TEM imaging, circuit repair, scanning ion microscopy, and scanning ion mass spectroscopy.[11]
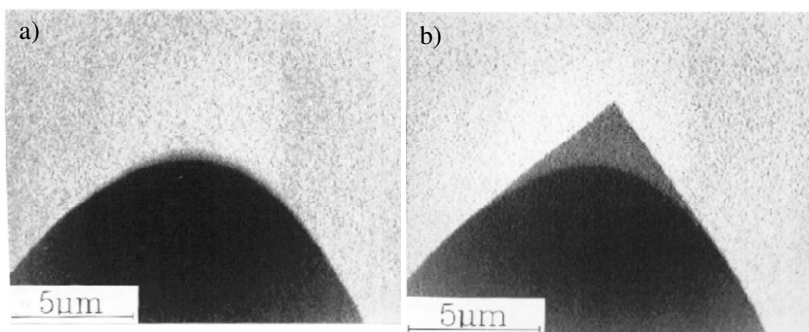
a)   b)

5μm   5μm

Figure 1. Image taken from Driesel's work showing an emitter tip a) without and b) with a Taylor cone.[12]

The research reported here takes advantage of Taylor cone formation in an effort to solidify, or quench, an operating LMIS to preserve the sharp ion-emitting jet-like protrusion for use as a field emission cathode for EP. The resulting metal structure has a tip radius of 10's to 100's of nanometers, which is ideal for Fowler-Nordheim emission. By reversing the polarity of the LMIS, the solid-metal tip will then function as a cold electron emitter.

While never applied to EP or space-based applications, the idea to use a liquid-metal Taylor cone as a combined electron/ion source is not new. The earliest documentation of a liquid-metal electron source (LMES) was the work of Swanson and Schwind.[13] Because the formation of a Taylor cone is independent of field polarity, Swanson and Schwind applied electron-extracting fields to a liquid metal in an effort to obtain electron emission from the liquid cone. They determined that stable electron emission was impossible to achieve from a liquid metal. In fact, they referred to the emission as explosive since small portions of the liquid metal were expelled as emission pulsed. The phenomena responsible for pulsed emission were supported by Gomer the following year.[14] Later on, using Ga and In, Rao et. al. found that it is possible to obtain DC electron emission if the LMES is first operated as an LMIS and then the Taylor cone is "frozen in".[15] It is now understood that, during operation as an LMIS, the Taylor cone forms a jet-like protrusion at the cone apex that can be solidified when the cone is quenched by removing heater power. It is the protrusion that is responsible for the stable electron emission when the extraction electrode polarity is changed to emit electrons.

In previous work, Makela and King showed the feasibility of creating field emitting tips from frozen Taylor cones by quenching the ion emitting jet-like protrusions at emission currents ranging from 0 to 25 μA. It was shown that an In emitter tip can be regenerated as long as there is a sufficient supply of In to obtain ion emission. It was also found that the electron I-V characteristics of a field emitter could be altered depending on how much heat is applied to liquefy the indium during ion emission and depending on what emission current at quench was chosen. It was found that quenching at higher ion emission current produced sharper emitter tip radii. Applying the Fowler-

Nordheim model to their electron I-V data yielded tip radii ranging from 80 to 230 nm at quench currents of 0 to 25 μA.[16]

II. Goal of Study

The research reported here focused on investigating the reproducibility of the jet-like protrusion formed when quenching an operating LMIS. The protrusion was used to generate electron emission I-V curves so that the Fowler-Nordheim model could be applied to estimate emitter tip radii. Tip radii were evaluated from protrusions formed at ion quenching currents ranging from 0 to 25 μA. Multiple tests are performed under the same conditions to address the repeatability of forming tips through Taylor cone quenching.

In an early effort to establish emitter lifetime, the electron source was operated over an extended period of time while keeping the extraction electrode in current-limited mode to observe how the extraction voltage varied over time. Before and after each experiment, electron I-V curves were taken to estimate tip wear rates and begin to evaluate the potential lifetime of the structures.

III. Description of Apparatus

For a number of reasons, it has become common practice to coat electrochemically etched tungsten electrodes with low-melting temperature metals to use as sites for Taylor cone formation. A couple of the reasons include the wetting and adhesion properties between the metals, as well as the ease of applying heat to the dual electron/ion source using resistive heating of the tungsten.[17] For the experiments reported here, sharpened tungsten electrodes with desirable geometry and surface features for electron and ion emission were formed using an electrochemical etching reaction involving a 200-mL solution of 2M NaOH and a 0.010"-diameter tungsten wire.   To electrochemically etch the tungsten, the wire was suspended in the center of a 250-mL cylindrical beaker with a cylindrical stainless-steel mesh placed along the perimeter of the beaker, as shown in the beaker cross section schematic in Figure 2.
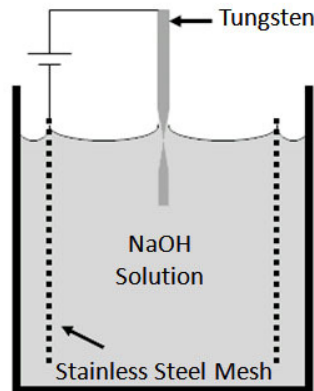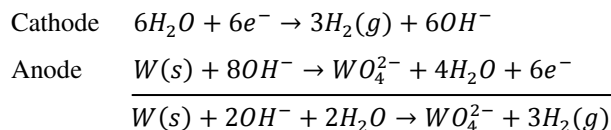

Figure 2. Electrochemical etching configuration.

By applying DC voltage between the partially submerged tungsten wire (anode) and the immersed stainless-steel electrode (cathode), the following reaction takes place at the air/electrolyte surface:[18]

$$\text{Cathode} \quad 6H_2O + 6e^- \rightarrow 3H_2(g) + 6OH^-$$

$$\text{Anode} \quad \underline{W(s) + 8OH^- \rightarrow WO_4^{2-} + 4H_2O + 6e^-}$$

$$W(s) + 2OH^- + 2H_2O \rightarrow WO_4^{2-} + 3H_2(g)$$

The reaction causes the oxidative dissolution of W to soluble tungstate (WO_4^{2-}) anions at the tungsten anode, as illustrated in Figure 3 and reduces the water to hydrogen gas bubbles and OH^- ions at the immersed stainless-steel cathode. This type of etching leaves a sharpened tungsten electrode with emitter tip radius of 10's to 100's of nm depending on the current and voltage chosen for the DC power supply.[18]
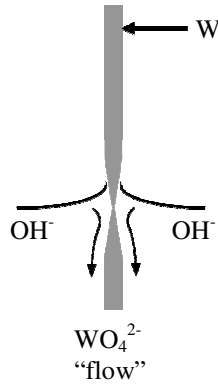
Figure 3. Schematic illustrating the "flow" of tungstate anions down the tungsten electrode in NaOH solution.[18]

The sharpened W electrodes were then coated with a layer of In by heating and then dipping the electrode in a crucible of liquefied In in a vacuum environment of 10^{-6} Torr. The etched and coated tungsten emitter was then inserted into a Teflon fixture that has a planar stainless-steel extraction electrode placed less than 0.5 mm away, as shown in the top view in Figure 4.
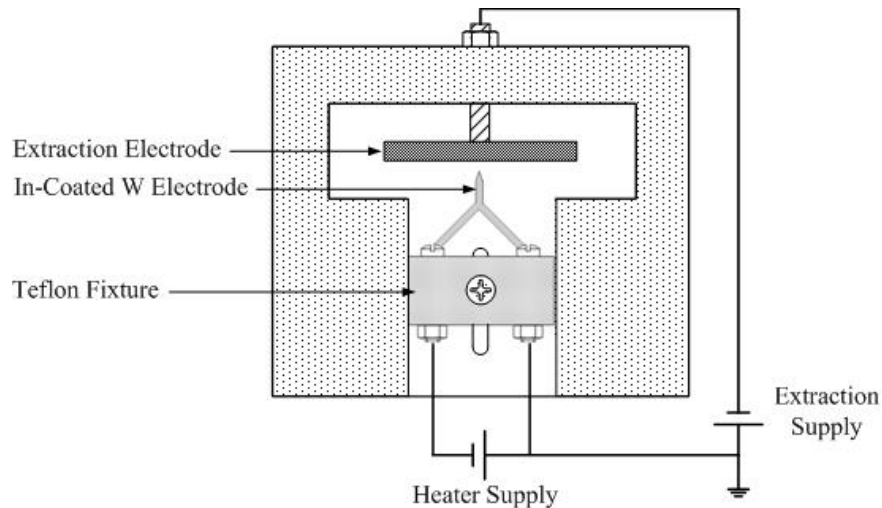

Figure 4. Dual ion/electron source electric schematic.

The entire assembly was then placed in the Ultra High Vacuum (UHV) chamber in the Ion Space Propulsion (Isp) lab at Michigan Technological University, shown in Figure 5. The UHV chamber is approximately 0.5 meters in diameter by 0.5 meters deep and has a base pressure of 10^{-9} Torr, which is achieved by pumping with a single 280-l/s turbo-molecular pump that is backed by a 110-l/min dry scroll pump. The tank is also equipped with a 300-l/s combination ion-sublimation pump to reach ultra-high vacuum. With the addition of the titanium sublimation pump (TSP) to the ion pump, higher pumping speeds are possible due to the TSP pump's ability to handle getterable gases.
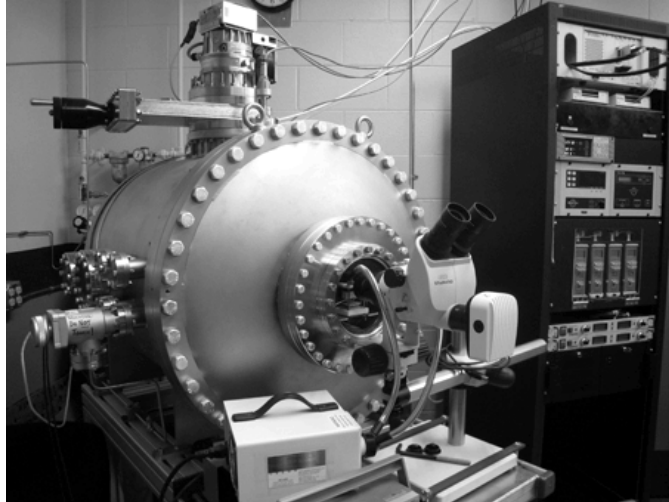
Figure 5. Image of the UHV chamber and the stereo microscope.

An additional feature of the UHV facility is a trinocular stereo microscope. The microscope is situated outside the front viewing port of the chamber and has a focal length that allows viewing within the chamber. The microscope has an optical magnification up to 90x and it is equipped with a color digital camera. The camera provides the ability to capture *in situ* images of an operating LMIS, as well as the ability to record video directly through USB 2.0.

IV.   Results

To obtain ion emission it is necessary to first liquefy the layer of In on the W electrode. To do this, the emitter heating supply, shown in Figure 4, was powered and increased to attain a suitable temperature for the indium to melt. For the experiments reported here, the heater power during ion emission remained between 1 and 1.25 Watts which corresponded to 2.4 to 2.5 Amps of heater current. The heater supplied enough power to keep the In liquefied, without heating it to vaporization. The extraction electrode was then biased with a negative high-voltage power supply and the emitter was grounded. The negative voltage was increased until ion emission was achieved, usually taking 3 to 4 kV for the onset of emission. At that point, the high-voltage power supply was current-limited at 2 μA, allowing the voltage to float where necessary to maintain ion field emission. The current-limited operation was maintained for the first 30 minutes; during this period ion emission stabilized at constant voltage. After the 30-minute period, the ion discharge current was then switched to voltage-limited mode. The extraction voltage could then be adjusted to obtain a desired ion emission current. At that point, the emitter heater power was quickly reduced to 0 Watts, causing the emission current to decrease to 0 μA in 2 to 3 seconds. Removing the heat source was done to quench a sharp jet-like protrusion.

Once a sharp emitter was formed by quenching, the extraction electrode was biased with a positive potential to obtain electron field emission from the cold needle. The extraction voltage was swept between 0 and the voltage necessary to obtain 0.5 μA of emission current, V_{max}. The sweep was done by using the analog controls of the high-voltage power supply. A step function was input to sweep the extraction voltage at 25 V intervals every second up to V_{max} while recording 1000 samples/sec of the emission current through the analog output of a micro-ammeter. The micro-ammeter was designed and built in the Isp Lab to measure a 0 to 100 μA signal floating up to 10 kV and optically isolate a calibrated output of 0 to 10 V corresponding to the current.

A range of ion emission current before quenching of 0 to 25 μA was explored to determine what effect quenching current had on the electron emission characteristics. The procedure for the first 25 experiments was to first obtain ion emission, then quench the emitter to solidify and preserve the jet-like protrusion, and then use the quenched protrusion to produce an electron emission I-V curve by sweeping the extraction voltage while recording the emission current. After the electron emission characteristics were established, the emitter heater was increased to 2 Watts for 25 to 30 seconds with no applied extraction voltage in an effort to flash heat the emitter tip and, hopefully, destroy the tip to prepare for re-formation in subsequent tests. It was initially thought that melting the indium on the emitter tip in the absence of an electric field would allow the surface tension of the liquefied indium

to destroy any sharp protrusions so that additional testing could be done to form new sharp tips at different quenching currents.

Upon further investigation using the optical microscope, it was obvious that merely increasing the amount of heat to the emitter wasn't removing the sharpened protrusions: subsequent tests were likely inducing emission from the same protrusion each time. This prevented a study of protrusion shape as a function of ion quench current, so a new method was conceived to destroy the emission site prior to re-growth. The new method involved increasing the extraction voltage to approximately two to three times what was necessary to achieve the maximum emission current of interest, 0.5 µA. This caused the emitter to briefly arc to the extraction electrode, a process that exploded the protrusion off of the emitter apex, giving off a micro-scale white flash. An image acquired using the microscope prior to removing the protrusion and the instant after removing the protrusion is shown in Figure 6.
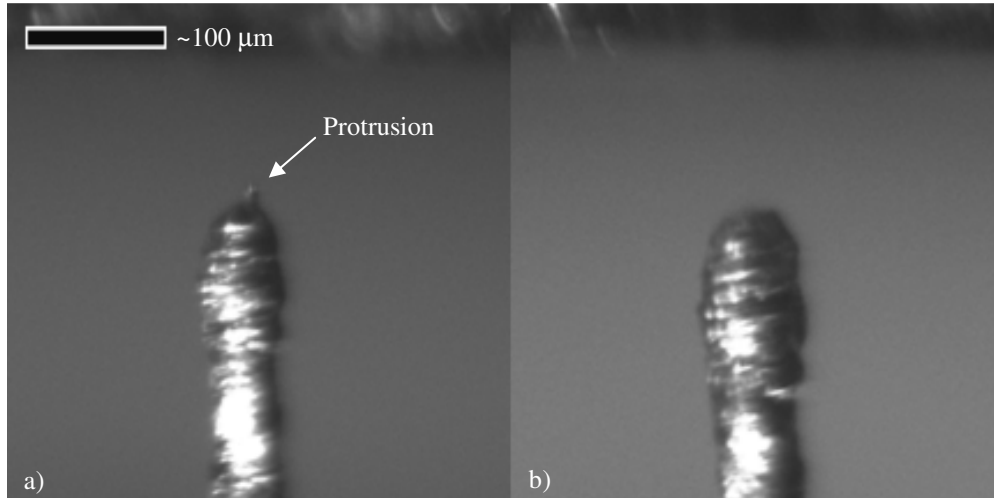

Figure 6. Microscopic images of an In coated W electrode with a) jet-like protrusion solidified and b) after the protrusion has been removed.

Once the new method of blunting the emitter tips was discovered, a new set of experiments were conducted ranging the ion emission current at quench between 0 and 25 µA. Just as previously done, the heater power was increased to approximately 1 Watt and then the extraction voltage was increased until ion emission began. Then the ion source was current-limited at 2 µA for 30 minutes. After the emission stabilized, the ion discharge current was switched to voltage-limited mode. The extraction voltage was then adjusted to achieve the desired emission current and then the heater power was decreased to 0 Watts, solidifying the jet-like protrusion. The polarity of the extraction electrode was then reversed to obtain electron field emission and swept from 0 to V_{max}. Multiple electron I-V curves are shown in Figure 7. Each curve was taken after quenching a jet-like protrusion at a different ion emission current. Between each successive test the tips were exposed to an increased electric field to explode the sharpened protrusions and then they were heated up to 2 Watts in an attempt to smooth out any additional protrusions.
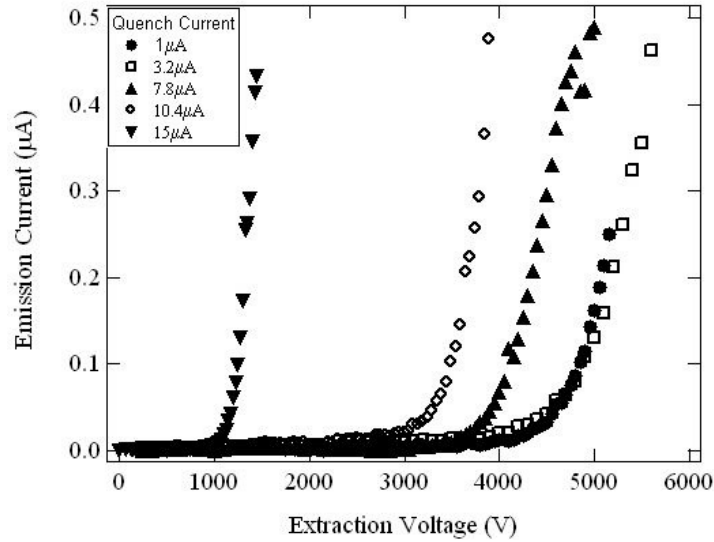
Figure 7. Electron emission current vs. extraction voltage for emitters quenched at different ion currents.

Additional data were then taken to determine characteristics of an emitter as it is operated over an extended period of time. First, a protrusion was formed at an ion emission quench current of 15 μA. Then, the emitter was operated for a total of 46 hours by current-limiting the electron emission at 1 μA and allowing the extraction voltage to increase or decrease as necessary to stably operate. The duration of the test was limited by the lifetime of the batteries in the micro-ammeter that was used to measure the discharge current. The extraction voltage at the start of the experiment was approximately 4 kV and slowly decreased to about 2.2 kV in the first 24 hours. The experiment was then stopped so that an electron I-V sweep could be taken to estimate the emitter tip radius. Then the experiment was restarted for another 22 hour time period. When the experiment was restarted it took nearly 5 kV applied to the extraction electrode to obtain 1 μA of electron emission current. The extraction voltage decreased throughout the next 26 hours to about 2.5 kV. The experiment was then stopped so that an electron I-V could be obtained to get an estimation of emitter tip radius. Another electron I-V was taken at the end of the test. All three of the curves are shown in Figure 8.
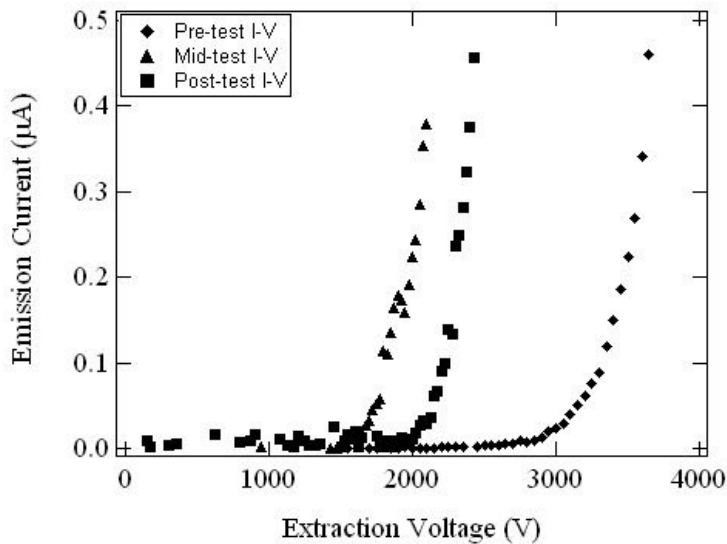

Figure 8. Electron I-V curves taken before a 46 hour test, 24 hours into the test, and at the end of the test.

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V. Discussion,

Using the electron I-V curves along with the Fowler-Nordheim equation it was possible to make a theoretical estimate of the emitter tip radius. For tip radius evaluation, Gomer's technique of applying the following Fowler-Nordheim equation was used,

$$\frac{I}{V^2} = a\,exp\left(\frac{-b'\phi^{3/2}}{V}\right) \qquad \text{Eqn. 1}$$

where a and b' are introduced as the following

$$a = A6.2 \times 10^6 (\mu/\phi)^{1/2}(\mu/\phi)^{-1}(\alpha kr)^{-2}, \qquad \text{Eqn. 2}$$

$$b' = 6.8 \times 10^7 \alpha kr \qquad \text{Eqn. 3}$$

In this series of equations I is the discharge current measured in Amperes, V is the extraction voltage measured in volts, ϕ is the work function in eV, A is the total emitting area, α is the Nordheim image-correction factor, and a and b' are curve fits corresponding to characteristics of the I-V data plotted as $\ln(I/V^2)$ versus I/V.[19]

When plotted, the graph of $\ln(I/V^2)$ versus I/V is linear, as shown in Figure 9, and has an intercept of $\ln(a)$ and a slope of $b'\phi^{3/2}$. Using Equation 3 and taking α to be 1 and k equal to 5 for a parabolic tip shape, the tip radius, r, can be approximated.[19] This was done for each of the quench conditions and is shown in Figure 10 and Figure 11.
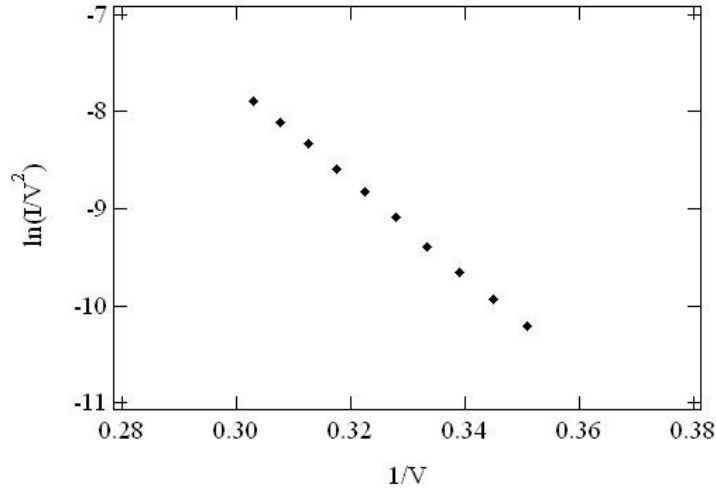

Figure 9. Fowler-Nordheim plot of electron field emission taken on a cold tip after quenching at a 15μA ion emission current.

A. Fowler-Nordheim Analysis from 1st Set of Experiments

As mentioned previously, after conducting numerous experiments at randomized quench currents falling in the range of 0 to 25 μA it became apparent that the majority of emitter tip radii predicted using Fowler-Nordheim modeling ranged between 6 and 12 nm as shown in Figure 10. Microscopic investigation revealed that the emission sites were not being adequately destroyed, or re-set, between tests. At this point, the new tip destruction technique was employed between successive experiments to cause the sharpened protrusion to arc so that a new protrusion could be formed at a different ion emission current.
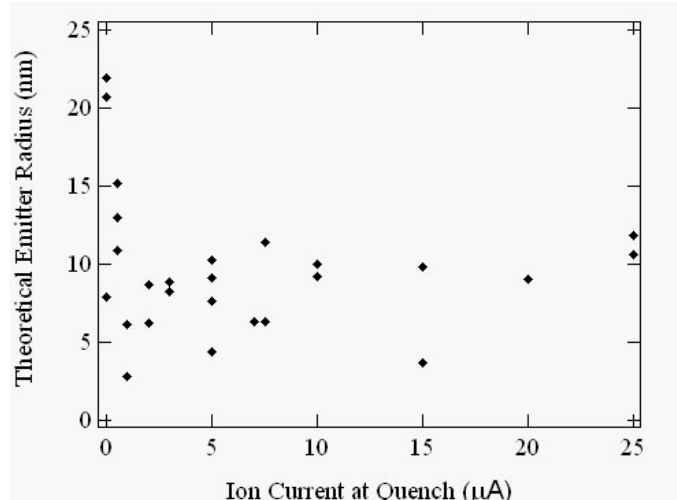
Figure 10. Estimated emitter tip radii using Fowler-Nordheim modeling at quenching currents ranging from 0 to 25 µA. These data were obtained using a failed technique to destroy the emitter tip between tests. All tests were likely emitting from the same micro-protrusion.

B. Fowler-Nordheim Analysis from 2nd Set of Experiments

The estimated tip radii using the Fowler-Nordheim analysis from this set of experiments has a more defined trend. It is clear from looking at Figure 11 that the emitter tip radius decreases as the ion current at quench is increased. This was expected from an examination of Figure 7. Sharper protrusions have much lower onset voltages, where onset voltage is defined as the extraction voltage where field emission begins.
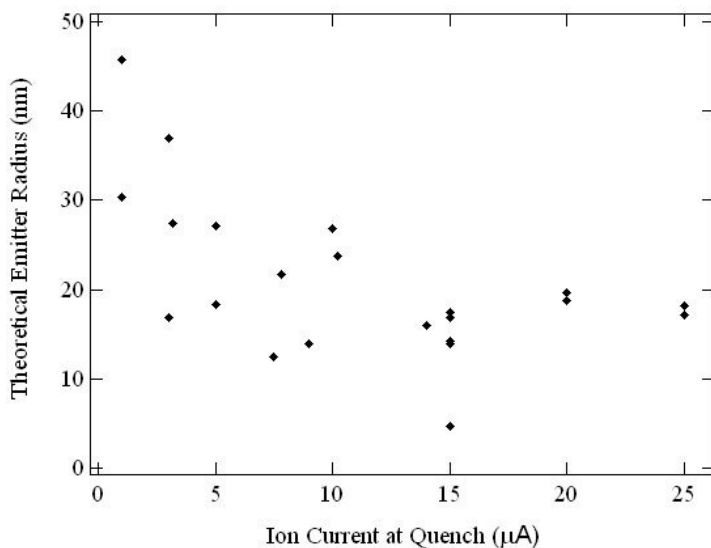

Figure 11. Estimated electron emitter radius using Fowler-Nordheim modeling at quenching currents ranging from 0 to 15 µA.

It has been shown that the ion emission current prior to quenching a jet-like protrusion has a large impact on the electron I-V characteristics when the polarity of the extraction electrode is reversed and the voltage is swept from 0 to a few kV. It is also clear that as the ion current before quench is increased, there is an increase in the electron emission at much lower extraction voltage. Since the local electric field at the emitter apex is approximated as,

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$$E_o = V/kr_t,$$ <div align="right">Eqn. 4</div>

where V is the applied potential, r_t is the tip radius, and k is a geometric factor that can be approximated as 5 for most emitters with a parabolic tip shape, it is clear to see that local field enhancement increases as the emitter tip radius decreases.[19] Therefore, it is safe to assume that as the ion current before quench increases there is a decrease in jet-like protrusion radius, which agrees with the Fowler-Nordheim model. The opposite trend was shown by Chen and Wang.[20]

After establishing that a relationship existed between ion quenching current and the emitter tip radius, multiple protrusions were formed at each quench current to determine tip reproducibility. The amount of scatter in the estimated emitter tip radii was approximately 15 nm at each quench current, as shown in Figure 11. From this limited data set it appears that once ion quenching currents of 15 µA are exceeded, the emitter tip radius reaches a minimum. This could be due to micro-droplet emission causing the tip to 'break' off from the emitter apex at higher emission currents.[21]

C. Extended Duration Experiment

To address tip lifetime for electron emission a protrusion was formed using a 15-µA ion current at quench. Electron emission was then sustained for a period of 46 hours. The emission was current-limited at 1 µA, allowing the extraction voltage to float wherever necessary to maintain the current set-point. At the beginning of the experiment the extraction voltage required to obtain 1 µA of emission was approximately 3.85 kV. The extraction voltage decreased over the 46-hour period to about 2.2 kV. That would imply that the emitter tip became sharper over the span of the test, although we have no direct evidence to support this nor can we envision a mechanism that would cause the tip to become more sharp. The electron I-V curves for the pre-test, mid-test, and post-test, shown in Figure 8, correspond to estimated tip radii using the Fowler-Nordheim model of approximately 18, 5, and 15 nm, respectively. Since it was thought that the emitter tip radius would increase over time, it is possible that the tip requires a certain amount of time to reach thermal equilibrium and 'warm-up'.

VI.   Conclusions

It was found that the ion quenching current has an important role in the geometry of the jet-like protrusion that is formed. By applying the Fowler-Nordheim model to the data that was collected it is apparent that higher quenching currents form sharper protrusions, which is what was expected when looking at the electron I-V curves after each quench. The electron I-V curves show that electron emission onsets at much lower extraction voltages from emitters that were quenched at higher currents. Also, it was found that emitter tips could be reproduced to within a range of about 15 nm at each ion quenching current.

The results of the 46 hour test were unexpected. The emitter tips were expected to degrade over a period of time but the emitter that was tested shows indication of the opposite. A much longer test would help to determine if the emitter needs a certain amount of time to 'warm-up' when emission is obtained.

To study the jet-like protrusions closer, another experiment will be done in the near future to operate the LMIS inside of a Field Emission-Scanning Electron Microscope (FE-SEM). A custom fixture has been designed and is currently being machined so that tip quenching experiments can be conducted inside of an FE-SEM while *in situ* imaging the jet-like protrusion ata nm-scale resolution. Results are anticipated during the fall of 2008 with data to be presented at the 2009 AIAA Joint Propulsion Conference.

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