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FIELD EMISSION CATHODES USED IN THE FEGI GET AWAY SPECIAL SHUTTLE MISSION

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Field emission cathodes are presently being developed as low-power space electric propulsion neutralizers and for spacecraft charge control and electrodynamic tether applications requiring no consumables. These cathodes effect cold electron emission by the application of a relatively high electric field across a small gap from some kind of electron emitting (cathode) surface. Various designs of field emission cathodes are being investigated for charge control on a student-built experiment called Field Emission Get-Away-Special Investigation (FEGI), including molybdenum, carbon nanotube, boron nitride and diamond surface emission cathodes. This paper presents the current progress of the FEGI experiment with a focus on the emitters that will be flown, and the immediately surrounding electrical, mechanical and environmental support structures.

Nomenclature

cBN = cubic Boron Nitride
CNT = Carbon Nanotube
FE = Field Emitter
FEGI = Field Emission Get-Away-Special Investigation
LEO = Low Earth Orbit
LVTF = Large Vacuum Test Facility
HCA = Hollow Cathode Assembly
KE = Kinetic Energy
SVPE = Small Vacuum Protective Enclosure
V_applied = Voltage applied to the electrostatic analyzer

I. Introduction

FIELD emission cathodes are being investigated for space applications in which electron beam emission is required at minimum expense of power and expendables (e.g. xenon gas). Traditional methods for charge control generally involve either a hollow cathode plasma contactor whereby charge is exchanged across a low voltage plasma sheath[1] or a thermionic emitter in the form of a high temperature filament. For some new spacecraft architectures, including electrodynamic tether systems and low-power electric propulsion thrusters, it is desired to achieve electron emission without the high power of a filament cathode or the gas expellant of a hollow cathode[2].

In comparison to thermionic emitters, such as are found in typical electron guns, field emission cathodes should be extremely power efficient, have lower mass, and tolerate higher contamination and outgassing pressures around the spacecraft otherwise associated with hot cathodes. In comparison to plasma contactors, field emitters (FE)

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should also be more power efficient, lower mass, and will not require a hot cathode[3]. More importantly, however, field emission cathodes require no expendables, another major obstacle associated with plasma contactors.

Students at the University of Michigan are constructing an in-space demonstration of field emitter technology in the form of a space shuttle Get Away Special experiment named FEGI: **F**ield **E**mitter **G**et-Away-Special **I**nvestigation. This experiment contains all the necessary power regulation, data handling, environment monitoring and contamination mitigation systems to automatically control and monitor up to twelve individual FEs. In addition, the design, the management and the construction of FEGI are under student control through U of M's Student Space Systems Fabrication Laboratory (S3FL). Major funding for the FEGI project is provided by the Air Force's University Nanosat program (sponsored also by NASA), The University of Michigan, The Pennsylvania State University, and Lockheed-Martin Corporation as well as instrument and emitter technology from the Air Force Academy, Busek Inc., The University of Michigan, NASA Marshall Space Flight Center, and the Air Force Research Laboratory (Hanscom AFB). Presented here is an update on the progress of the FEGI project, with an emphasis on the selection and testing of field emitter devices and supporting environmental sensors.

II. The FEGI Mission

The Field Emission Get-Away-Special Investigation consists of three Small Vacuum Protective Enclosures (SVPEs) each housing 3-4 individual FEs. Upon reaching orbit, the SVPEs will open following sufficient outgassing time and the constraints of primary payload operations, thereby exposing the FEs to the local space plasma. Field emission experiments will commence, with measurements being made of gate and tip current, electron return current, and ambient plasma conditions to evaluate the effect of the plasma on FE emission and vice versa. Once FEGI has reached its estimated maximum battery lifetime of 24 hours, the SVPEs will be re-sealed for inspection upon return to earth. The primary benefits of the Get Away Special shuttle architecture include low cost, well defined electrical and mechanical interfaces, little reliance on external power or data interface and a returnable, reusable payload. In addition, the Space Shuttle environment can be considered a worst-case scenario for the operation of these field emission cathodes with high contaminant and atomic oxygen fluxes. If the FEs will work on the shuttle, they will arguably work anywhere.

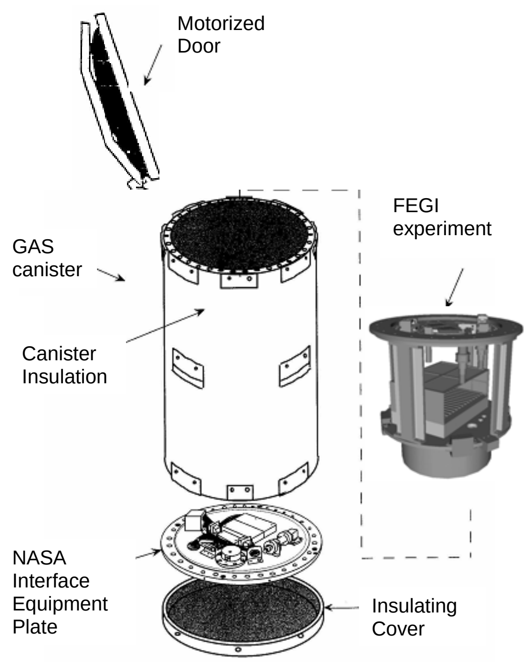

Figure 1. FEGI Get Away Special payload. *Also shown: interface with the NASA-supplied Get-Away-Special canister.*

A. Field Emitters Considered

At least four field emitter technologies are planned to be flown on the FEGI experiment, each conforming to a consistent form factor and electrical interface on a TO-5 header. Device technologies include: Spindt-type cathodes[4], Carbon Nanotube (CNT) Field Emission cathodes from Busek, cubic Boron Nitride (cBN) cathodes developed at Michigan[5] and Diamond Surface Emission cathodes being developed at Lincoln Lab/Hanscom AFB[6]. Each of these technologies has characteristics making them more or less suitable for in-space propulsion and charge control; FEGI will provide a platform for the parametric study of each device in the low-earth space environment. Parameters that will be monitored include emission charge density, atomic oxygen sensitivity, contamination susceptibility and ease of ground handling and system integration.

1. Spindt-type Cathodes

These well known devices are fabricated by SRI International and consist of micrometer-diameter emitting cones etched into a Molybdenum substrate, with a surrounding gate electrode. The small gate-tip separation allows high current densities, approximately 1-2 A/cm^2 at gate-tip bias levels less than 100 V making these perhaps the most efficient FEs on the market today. The low voltages required to operate these devices also reduces the energy of incident sputtering ions, which could result in an increased operational lifetime.

One significant limitation of this technology is its sensitivity to ambient pressure. While Spindt-type cathodes have already been spaceflight qualified for use in vacuum tubes, recent low-vacuum tests[7] have shown performance and lifetime shortages when background pressures rise above $1x10^{-7}$ Torr, especially if significant partial pressures of oxygen are present. However, there is ongoing research in surface coatings that can improve their performance.[8]

2. Carbon Nanotube (CNT) Cathode

Carbon Nanotubes (CNT) are important new field emitting materials, which have been proposed as electron sources for several space-based applications including miniature X-ray tubes and Field Emission Electric Propulsion (FEEP) cathodes. These emitters have shown sustainable current densities up to $1A/cm^2$ at electric fields under 8V/µm and higher system efficiency than hollow cathodes[9].

The CNT Field Emission cathodes used on FEGI will be a custom device supplied by Busek Inc. to conform to interface standards and a form factor consistent with a TO-5 header (and Spindt cathode). Busek is already developing small flight-qualifiable CNT devices for low-power electric propulsion applications. Unlike the highly aligned gate-tip combinations of the Spindt-type cathode, the CNT cathode's mesh grid is suspended several micrometers above its film of randomly oriented CNT segments. The relative increase in separation distance raises the bias required to achieve a similar surface electric field and emission current density. For instance, the CNT emitter will achieve a cathode current of 0.6 mA with a 470V bias as opposed to 70V for a standard Spindt device. The gate current collected by the CNT emitter will also be greater than by the Spindt emitter due to its random orientation of emission sites. This will in turn decrease the emitter efficiency, requiring higher power draw for each amp of emitted current. However, for certain low-power applications that Busek is pursuing, the lower efficiency is acceptable.

Our laboratory tests do show these devices to be more robust than Spindt-type cathodes at higher background pressures. In fact, storage of these devices at atmospheric pressure is not a problem which suggests that spacecraft integration and handling issues will be less of a concern. Single gate-tip shorting events are still possible due to surface contamination, so the SVPE should protect against that. Long-term degradation of the CNT emitters has also been documented, and stems from field evaporation, ion bombardment from the gas phase, or from selective oxidation[10]. FEGI will provide in-space testing of these devices to show their applicability in low-earth orbit and in the space shuttle environment.

3. Cubic Boron Nitride emitter

Thin films of polycrystalline cubic boron nitride (cBN) have been synthesized using the reduced-bias ion-assisted sputtering technique[11]. These large bandgap films have shown effective field emission and are also theorized to resist contamination and atomic oxygen disruption. Recent tests at Michigan suggest resilience to O_2, H_20 vapor, and Xe in pressures of approximately 10^{-6} Torr. Preliminary data of the films grown on Si (100) substrates suggests a low emission threshold of ~2.75 V/µm.[12] Cubic Boron Nitride films would make effective field emitters on their own, or as a potential coating atop a Spindt-type cathode (Moly or Si tips).

Integrated devices are under development at the University of Michigan using a microstructured gate and insulator, which is placed atop a cBN thin-film deposited onto Si substrate as a tipless technology. This combination allows a moderate bias to be placed at the accelerating gate 0.5 – 2 micrometers away from the emitting surface, while still obtaining the high electric field required to achieve electron emission from the Boron Nitride thin film. The microstructured conductor and insulator allows accurate gap spacing between the gate and emitting surface, and reduces both the gate current and the likelihood of catastrophic shorting between the gate and emitting surface.

4. Diamond Surface Emission Cathode

High electric fields can be obtained at the three-way intersection of a semiconductor surface, a metal cathode and vacuum (a so-called triple junction). Surface-emission devices rely on a positive space charge forming in the semiconductor surface to enhance the bias applied at the metal cathode. Extremely high electric fields, ~ 10^8 V/cm, can be generated in this way which will pull electrons from the metal electrodes into vacuum. Prototype devices have been fabricated to maximize this triple junction with a geometrically optimized metal gate deposited onto a doped diamond substrate. Recent 2mm long devices have generated >100mA/cm emission current at 200V[13].

This is a brand new technology and to this point has little experimental data to describe its operation in non-ideal conditions. Because the structure consists of a metallized diamond thin-film, it should be quite robust. The distributed metal cathode should also make it resist contaminants and sputtering, and short-circuit is only possible once the breakdown potential of diamond is reached. The low velocity with which the electrons are emitted from a surface emission cathode could lead to a space-charge limited electron beam, but a higher electron current could be accommodated by a neutralizing ambient plasma ram current.

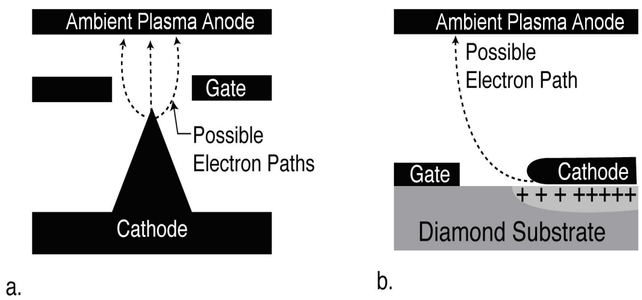

Figure 2. Spindt Field Emitter Array cathode (a.) and Diamond Surface Emission cathode (b.) *In (b.) a negative bias applied to the cathode results in positive surface charge in the substrate, leading to surface electric fields high enough to pull electrons from the conduction band of the cathode.* Ref. 13

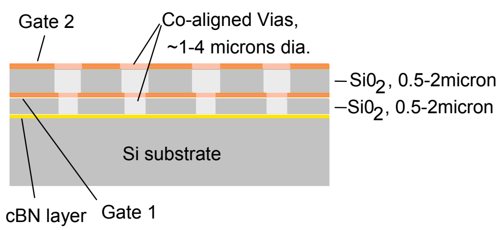

Figure 3. Diagram of Cubic Boron Nitride "Planar" Field Emitter Cathode. *Including possible multilayered microstructured gate and insulator developed at the University of Michigan.*

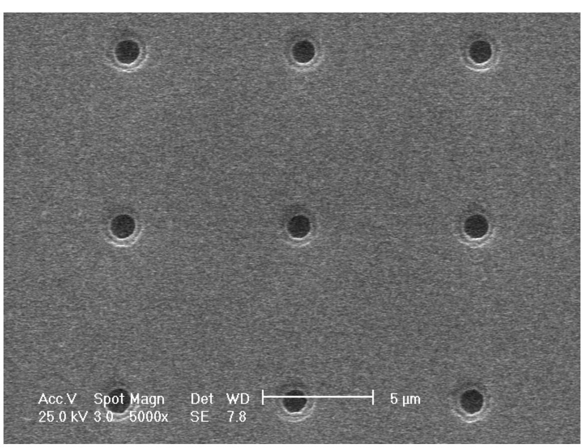

Figure 4. SEM picture of the microstructured gate/insulator portion of the cubic Boron Nitride "Planar" Field Emitter Cathode

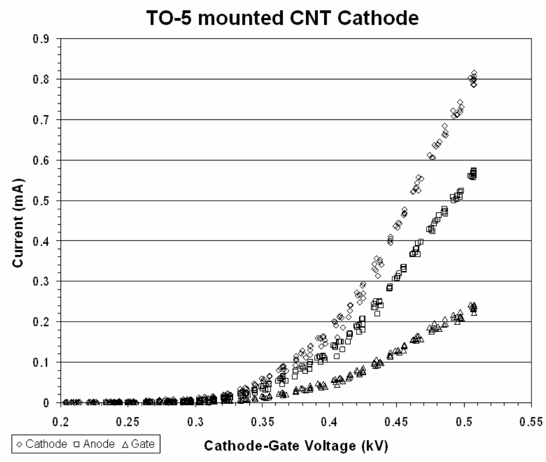

Figure 5. TO-5 mounted CNT Cathode I-V data. *Manufactured and tested by Busek Inc. The device has an active emitting area of 0.3 cm² with emission density reaching 0.004A/cm² at 500V in this test.*

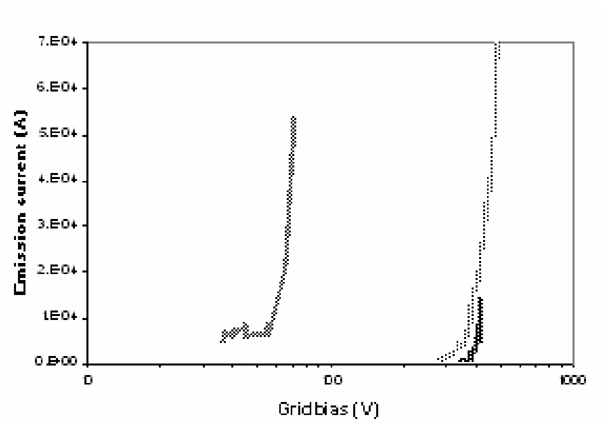

Figure 6: Emission current from a Spindt cathode and Busek CNT cathode. *I-V data for Spindt FE (left curve), Busek CNT cathode characterized by manufacturer (middle curve), and Busek CNT cathode I-V curve taken at U of M (right curve). Both devices are mounted on the same 6mm diameter TO-5 header form-factor.*

B. High voltage supply and monitoring

The primary science objective for the FEGI experiment is to achieve electron emission with various emitter technologies, and also to get the electron current away from the host spacecraft. This objective will be shown by current and voltage measurements on the gate and cathode line of each FE. Since electrons will be emitted directly into the plasma environment rather than to a stationary anode, the net emission current will have to be implied indirectly from total current leaving emission sites less current collected at the gate and returned to the surrounding structure. It is from this data that we will evaluate the operation of each field emitter.

In order to deal with the likely occurrence of one or more of the FE's developing a gate-tip short circuit, we are including redundancy and short circuit clearing capability in our design. Redundancy in our primary mission will be provided in several ways- by flying multiple samples of each emitter technology, and by including redundant high-voltage power supplies, measurement and switching capability. Short circuit cleaning will be accomplished in several ways- by charging and discharging a 1 micro-Farad capacitor across the gate and tip of the device, and by incrementally increasing the current supplied to the device in hopes that resistive heating will boil off any bridging conductor. Further testing will help to develop an algorithm that can be used in a computer automated experiment to consistently revive a shorted device.

Also, adsorbed surface contaminants can be removed by the method proposed by Schwoebel et al.[14] namely by Joule heating of the cathode. This is accomplished by either pulsing current to the cathode, or in our case by biasing both gate and tip positively by several hundred volts. The attraction of ambient electrons from the surrounding plasma leads to local heating and surface contaminant desorption.

C. Proximal data collection

Secondary instruments will be included on the FEGI mission to characterize electron current returning to the spacecraft due to space charge limits. Detection will include spatial and kinetic energy distribution of returning electrons, the first provided by segmented current collecting plates, the second by a flat plate Miniature Electrostatic Analyzer (MESA) developed at the Air Force Academy. The MESA instrument is an electrostatic analyzer designed to measure fluxes of electrons with KE from zero up to greater than 100 eV. This analyzer has a small form factor of 80mm x 80mm x 5mm, and electronics to allow picoamp level detection of both ambient thermal electrons and high speed emission electrons. Electrons of different speeds are passed through the MESA electron optics by applying a selection bias V_applied. A biased plate collects these selected electrons and gives a voltage response. Experimental calibration of the electrostatic analyzer was accomplished by comparing the kinetic energy distribution of a monoenergetic electron beam and Spindt type cathode with theory. The MESA device was determined to have an analyzer constant (actual KE / V_applied) of 1.35.

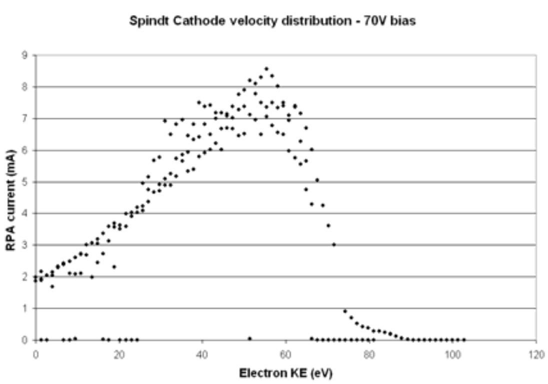

Figure 7 Spindt Cathode kinetic energy distribution *detected with an Air Force Academy supplied electrostatic analyzer – Miniature Electrostatic Analyzer (MESA) with an analyzer constant of 1.35.*

Other instruments will be flown to record environmental data useful to correlate with FE emission efficiency. An ionizing vacuum gauge will detect neutral gas pressure in the shuttle bay down to $1x10^{-7}$ Torr, to detect any contaminating events like a shuttle water dump. A sacrificial pyrolitic graphite coupon similar to one flown on a previous shuttle mission[15] will be included to record the extent of atomic oxygen damage seen throughout the mission. Also, several contamination witness coupons will be included to keep a record of any non-volatile residue e.g. hydrocarbon oil and debris that may hinder field emitter operation. These contamination coupons will be analyzed post-flight via Diffuse-Reflectance Infrared Fourier Transform (DRIFT) Spectroscopy to determine the thin-film contaminant's atomic and molecular constituency.

D. Environmental protection:

The centerpieces of the FEGI mission are the three SVPE vacuum vessels used to house up to 4 field emitter devices apiece. These small vacuum protective enclosures remains closed before and after experimentation, and will provide an air-tight seal to prevent contamination by H_2O, oxygen and other sources prior to launch, and during re-entry. This precaution is necessary both to prolong the lifetime of the FE devices on-orbit, and to preserve any contaminants acquired on-orbit for post-mission analysis.

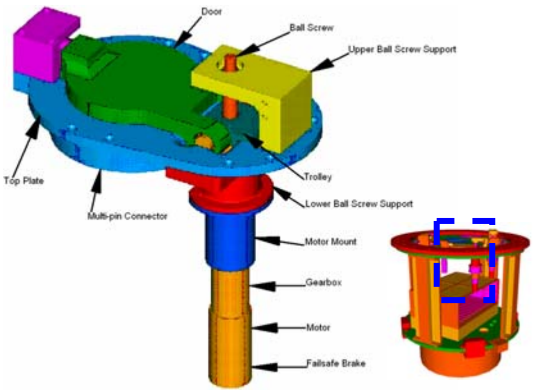

Figure 8. Small vacuum protective enclosure. *This motorized pressure vessel is designed to protect field emitters from contaminants in transit.*

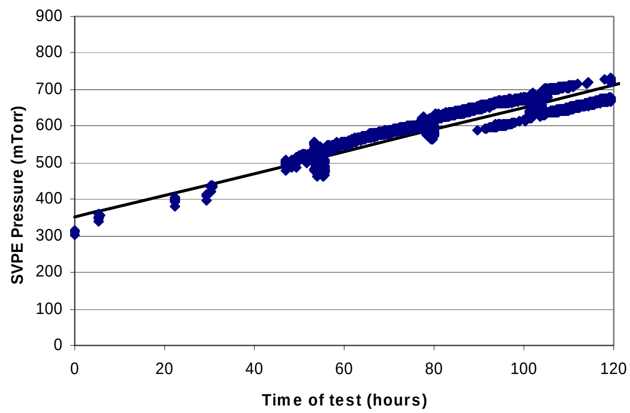

Figure 9. SVPE prototype leak rate. *The interior pressure as detected by a micro Pirani gauge shows a leak rate of 3mTorr / hour*

The SVPE is constructed with a vacuum flange electrical feed-through, a steel cylinder casing, a rotating door and motor assembly, and a field emitter mount, shown in figure 8. A DuPont Viton O-ring maintains a vacuum seal down to $1x10^{-6}$ Torr. The electrical feedthrough is a 41-pin conflat vacuum flange providing electrical connections to the field emitters and current collecting plates inside the SVPE.

Vacuum leak testing was completed on a prototype enclosure and was shown to maintain millitorr- level pressures for weeks. The vacuum measurement was accomplished by installing a micro Pirani gauge developed by Stark et al.[16] into the SVPE. This micro pressure sensor performs millitorr pressure measurement while only requiring a 1mm x 1mm device form factor and is being considered for integration into FEGI's final design for non-intrusive measurement of the SVPE vacuum levels.

The prior test, shown in figure 9, shows a leak rate of $4x10^{-5}$ torr-cm^3/sec which is adequate to keep particulate contaminants out. However, oxygen and water vapor can still leak in and adsorb onto Spindt cathode surfaces, which will degrade their performance. Further improvements will be made in the SVPE's final design, getting closer to the goal of a sub-millitorr vacuum seal for up to two months, which will protect the FE's during final integration and launch of the FEGI experiment. This is understandably a difficult goal to achieve. In addition to requiring a hermetic seal, the SVPE could not be a contamination source itself, and was constructed using all ultra-high vacuum materials.

III. Future experiments

More component testing will occur as more of FEGI's systems get built. In particular, the SVPE will be developed and shown to hold vacuum over longer periods of time, allowing it to be used to store various FE samples during further emission characterization experiments. Samples will be obtained of a cubic Boron Nitride emitter, and a diamond surface emission cathode, and their I-V characteristics will be determined. Additional Spindt cathodes and CNT cathodes will also be tested using automated current-ramping and fault recovery algorithms run by FEGI's command and data handling computer.

Integrated testing will detect any interface problems with disparate emitters stored in the same vacuum container and emitting in close proximity to the SVPE structure. It is possible that materials incompatibilities require certain emitter combinations to be stored and operated separately to avoid cross-contamination. The structure of the SVPE too could influence electron beam shaping and net emission current levels.

Future testing in a plasma environment is also planned to show the effects of a plasma anode on field emission patterns and the amount of return current in a non-space charge limited experiment. Current laboratory experiments require a collecting anode to prevent all emitted current from returning back to the highly biased accelerating grid. The effect of replacing this anode with an ionosphere-like plasma medium to absorb emitted charge is unknown. One proposed experiment in the Large Vacuum Facility (LVTF) at Michigan's Plasmadynamic and Electric Propulsion Lab includes using a hollow cathode assembly to provide a plasma environment closely approximating that of the ionosphere[17], and a field emitter mounted inside the SVPE to produce in interacting electron beam.

IV. Conclusion

Field emission cathodes have the potential to allow significant reductions in power, mass and consumables for in-space propulsion systems. Several mature FE technologies already exist that have been designed to operate in space, and require a low risk prototype testing platform. The FEGI experiment will be this first in-space test of FE devices exposed to a LEO environment. The FEGI architecture is modular, reusable, and compatible with most current FE devices, and provides a consistent testing environment to benchmark many emitter technologies. Data from the FEGI experiment will assist in flight qualification of many field emission cathodes and will help to determine the relative merit of different FE designs. As a student project, this experiment also introduces hundreds of future engineers to the art and science of spacecraft design.

Acknowledgments

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References

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[1] Patterson, M.J., "Hollow cathode-based plasma contactor experiments for electrodynamic tether" *AIAA Aerospace Sciences Meeting*, Washington D.C., 1987

[2] Gilchrist, B.E., Jensen, K.L., Gallimore, A.D., and Severns, J.G., "Space Based Applications for FEA Cathodes (FEAC)," *Materials Research Society Symposium Proceedings*, Vol. 621, 2000.

[3] Aguero, V.M. and Adamo, R.C., "Space Applications of Spindt Cathode Field Emission Arrays" Spacecraft Charging Technology Conference, Air Force Research Lab AFRL-VS-TR-20001578, 2000, pp. 347-352

[4] Spindt, C. A., "A thin-film field-emission cathode", *Journal of Applied Physics*, *39*, (7), 3504, June 1968

[5] Goldberg, H., Encarnacion, P., Morris, D., Gilchrist, B., Clarke, R., and Van Noord, J., "Cold-Cathode Electron Field Emission of Boron Nitride Thin Film with a MEMS-Based Gate for Space Applications", AIAA Joint Propulsion Conference 2004-3499, AIAA, Washington D.C., 2004 (not yet published)

[6] Geis, M.W., et.al, "A new surface electron-emission mechanism in diamond cathodes" *Nature* vol 393 Jun 4, 1998

[7] Tajmar, M.: "Survey on FEEP Neutralizer Options" *AIAA Joint Propulsion Conference 2002-4243* AIAA, Washington D.C., 2002

[8] Marrese, C.M., Gallimore, A.D., Mackie, W.A., and Evans, D.E., "The design of a cathode to operate in an oxygen-rich environment", Space Technology and Applications International Forum, AIP conference proceedings vol. 387, pp. 305-310, 1997

[9] Sarrazin P., et al.., "Carbon-Nanotube Field Emission X-Ray Tube for Space Exploration XRD/XRF instrument" *Denver X-ray Conference,* ICDD, Newton Square, PA, 2004 (to be published)

[10] Bonard, J., and Klinke C. "Degradation and failure of carbon nanotube field emitters," Physical review B vol. 67 number 115406, 2003

[11] Litvinov, D., Taylor, C. A. II, and Clarke, R., "Semiconducting cubic boron nitride" Diamond and Related Materials, vol. 7, pp.360-364,1998

[12] Encarnación, P. A. et al., "Electron Field Emission of Cubic Boron Nitride Thin Films" proc. 6th Applied Diamond Conference, 2001

[13] Cooke, D.L., Geis, M.W., "Introducing The Passive Anode Surface Emission Cathode", *AIAA Joint Propulsion Conference 2002-4049* AIAA, Washington D.C., 2002

[14] Schwoebel, P.R., Olson, R.T., Panitz, J.A., and Brodei, A.D., "In situ cleaning of microfabricated field emitter cathodes", Journal of Vacuum Science and Technology B, vol. 18, no. 5, pp. 2579 – 2582, 2000

[15] Ngo, T., Snyder, E.J., Tong, W.M., Williams, R.S., and Anderson, M.S., "O atom etching of graphite in low earth orbit" *Surface Science Letters*, vol. 314 number 1, pp. L817-L822, 1994

[16] Stark, B. H., Mei,Y., Zhang, C., and Najafi, K., "A Doubly Anchored Surface Micromachined Pirani Gauge for Vacuum Package Characterization," *16th International Conference on Microelectromechanical Systems*, IEEE, Kyoto, Japan, pp. 506-9, 2003

[17] Bilen, S.G., Domonkos, M.T., and Gallimore, A.D., “The Far-Field Plasma Environment of a Hollow Cathode Assembly”, AIAA Joint Propulsion Conference 1999-2861, AIAA, Washington D.C., 1999