In-FEEP Thruster Ion Beam Neutralization with Thermionic and Field Emission Cathodes[1]

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Charge neutralization of an In-FEEP thruster was demonstrated with three different electron sources by zeroing the floating potential of the thruster and neutralizer system. The three cathodes used in the investigation include a mixed metal thermionic cathode, a carbon nanotube field emission cathode, and a Spindt-type Mo field emission array cathode. The field emission cathodes significantly improved the power to thrust ratio of the thruster and neutralizer system. At 10 μN, the power-to-thrust ratio of the ion and electron source FEEP system decreased by 50% when the Spindt-type cathode was used. Measured plasma potential profiles were consistent with theoretical results obtained previously.

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Nomenclature

I_{ES} = Electron source beam current
I_{IS} = Ion source beam current
P_D = Discharge power (ion current and total voltage between the ion and electron emitters)
P_{ESG} = Electron source gate power
P_{ESH} = Electron source heater power
P_{ISG} = Ion source gate power
P_{ISH} = Ion source heater power
P_S = Total power
T = Thrust
V_{BT} = Beam target voltage
V_{ESG} = Electron source gate voltage with respect to the emitter
V_{FFEEP} = Floating potential of the thruster common
V_{ISG} = Ion source gate voltage

Introduction

Field Emission Electric Propulsion (FEEP) thrusters are under development for missions requiring μN thrust level control.[1] Two different designs have evolved using either indium or cesium as propellant. In-FEEP thrusters were originally developed by the Austrian Research Centers (ARC) in Seibersdorf as ion sources for spacecraft charge control instruments and successfully flown on a number of missions throughout the 1990s and most recently on the CLUSTER-II mission which has been in orbit since August 2000. [2] Cs-FEEP thrusters have been under development for propulsion applications since the 1970s at ESTEC, SEP and CENTROSPAZIO. The advantages and disadvantages of Cs and In propellant have been debated extensively. [3] Because of their high electrical efficiency, specific impulse, and thrust controllability, FEEP thrusters have been given serious consideration for attitude and orbit control of small spacecraft [4] and as disturbance reduction systems on a formation flying spacecraft like the Laser Interferometer Space Antenna (LISA).

Recently, the In-FEEP thruster development effort has been focused on demonstrating higher technology readiness levels. Direct thrust measurements were recently acquired at JPL. A 4000-hour life test at 2 μN and a 820-hour life test at 17 μN were recently completed. 500 hours were demonstrated using profiles up to 60 μN. [5] Microdroplet and neutralizer contamination studies have been underway at ARCS and modeling efforts at ARCS have been focused on plume characteristics and interactions with spacecraft. The plasma potential in the plume was modeled to show that positive space charge near the tip does not form a virtual anode which could stall the ion beam. [6] It has also been shown that the neutralizer had little effect on the plasma plume potentials. [7] The electrons which are emitted at a distance of at least several centimeters from the ion emitter do not interact significantly with the primary ions because of the large ion number density gradients near the thruster. Therefore, neutralizer effects on the plasma plume potentials were believed to be minor. This investigation is important in determining whether a neutralizer cathode is required to neutralize the ion beam space charge and/or the spacecraft charge.

Thermionic cathodes have traditionally been used as neutralizers with In-FEEP thrusters although more efficient cathode technologies should be compatible with these thrusters. The Thales-Thompson mixed metal thermionic cathode consumes up to 5.5 W for 15 mA of emitted current. The heater power required is independent of neutralizer current in some operating regimes. Therefore the efficiency of the cathode varies from 15 W/mA at 100 μA to 0.36 W/mA at 15 mA. Spindt-type field emission cathodes have demonstrated 180 mA at 120 V with <1 mW consumed by the gate electrode for a performance of <8 mW/mA without propellant or heater requirements. Power consumption by this cathode reduces with decreasing current. At this operating point, the current density from the 0.78 mm^2 emitting area of 50,000 tips was 23 A/cm^2. These cathodes commonly demonstrate 10 mA at 100 V.

The focus of this investigation was to experimentally determine the potential profile in the plume and evaluate the performance of three different neutralizers with the thruster. The plasma potential profiles were measured with an emissive probe in a UHV facility in configurations with the thruster electrically grounded or floating and the beam target grounded or biased to suppress secondary electron emission. The thruster and neutralizer were electronically shorted or floating with respect to ground to investigate the neutralizer current required to zero the floating potential of the propulsion system. These measurements were performed with a mixed metal thermionic cathode, a CNT cathode, and a Spindt-type cathode to determine whether all of these cathodes are compatible with the

In-FEEP thruster and the performance advantages of each of them.

In this article, the experimental apparatus are described, the results are presented, and the conclusions are discussed. Also, recommendations are made for future investigations into ion and electron beam interactions in the In-FEEP thruster plume.

Experimental Apparatus and Method

In-FEEP Thruster

The In-FEEP thruster employed in these investigations was fabricated, provided and operated by ARC Seibersdorf Research. [1] The configuration of the thruster consists of a tungsten needle, which is about 1 mm behind an extraction electrode with a 3.5 mm diameter aperture, in an In-filled reservoir. The configuration of the emitter is shown in Figure 1. The extraction electrode is electrically tied to thruster common and the needle emitter is biased positively with respect to the extraction electrode. The propellant is heated from a solid state to a liquid state and wicked up the needle shank to the tip where high electric fields deform the liquid and extract ions and accelerate them up to 130 km/s through 10 kV. Single emitter tip In-FEEP thrusters have demonstrated 0.1-120 μN of thrust with 0.1-1000 μA of current at 3-12 kV.

Cathodes

Three cathodes were used in these investigations into the In-FEEP thruster ion charge neutralization. The cathode extraction electrodes were positioned flush with the thruster body in the same position during each of the experiments. The electron extraction electrodes were always electrically tied to thruster common and the emitting surface was based negatively with respect to thruster common as Figure 2 shows. Each of the cathodes employed are described in detail in this section of the article.

Thermionic

A Thales-Thompson M-44 mixed metal thermionic dispenser cathode was provided by ARC Seibersdorf research for the experiments. The emitter is a porous tungsten-osmium matrix impregnated with Ba- and Ca-aluminates. Figure 3 shows the thermionic cathode employed in these experiments. Thermionic cathodes emit electrons with high enough thermal energies to get over the potential barrier between the emitting material and vacuum. This potential barrier can be reduced by lowering the work function of the material. Heaters are required to elevate the emitter material to the temperatures required to facilitate this process. This cathode can emit up to 15 mA with only 5.5 W of heating power. At constant heater power, the emitted current is controlled with the extraction voltage.

A similar cathode has been flown on several spacecraft and tested extensively at Seibersdorf Research to investigate its compatibility with In-FEEP thrusters. The cathode employed in these experiments was not tested at JPL before it was mounted to the In-FEEP thruster flange for these experiments. At ARC it has accumulated more than 170 hours of continuous operation. A similar cathode manufactured by PHILIPS was tested together with the In-FEEP thruster for several hours. The results of contamination studies performed at ARCS have shown that the performance of the cathode is affected by the environment when the cathode is operating in air with pressures above 10^{-6} Torr.

Carbon Nanotube

A carbon nanotube cathode, #A1E161B, was provided by FEPET Inc. for the experiments. The general configuration of the cathode is shown in Figure 4a. The carbon nanotube array , shown in Figure 4b, is grown on a silicon base with a chemical vapor deposition process. The invar mesh gate is isolated from the base by a ~75 um insulator. The field emission cathodes require high electric fields, $>4x10^7$ V/cm ,to deform the potential barrier at the vacuum-metal interface and enable cold electrons to tunnel into the vacuum. The carbon nanotube structure provides geometric enhancement of the electric field applied between the emitters and the extraction (gate) electrode. The cathode is shown in Figure 4 with the In-FEEP thruster.

The cathode configuration employed is an experimental model with very few hours of testing. It is under development as a neutralizer for several different electric propulsion systems and flat panel displays. This cathode was not tested at JPL before it was mounted to the FEEP thruster flange for these experiments. The performance of this cathode was characterized at FEPET Inc. It demonstrated 160 μA at 380 V on the gate electrode with 1.3 mA collected by the gate electrode.

The efficiency of this cathode has been demonstrated to be better than thermionic cathodes at μA current levels, however, its performance may more sensitive to the environmental conditions. The tubes can get sputtered by ions generated near the tips in electron bombardment ionization collisions. Ionized oxygen can react with the carbon to form volatile species. Some research results by other organizations have shown that carbon nanotube cathodes are more stable than Spindt-type cathodes and the materials commonly employed. [8,9] However, they typically require much higher operating voltages and operate less efficiently because of gate currents that are commonly 20% of the emitted current.

Spindt-type Field Emission Array

The Spindt-type field emission cathode, #1106E, provided by JPL from SRI International is shown in Figure 5. Figure 6a shows the cathode and thruster mounted to an 8-inch flange for the experiments. This type of cathode has been underdevelopment for flat panel displays and microscale instruments since 1961. [10,11] It was microfabricated with the integrated gate structure shown in Figure 5. The circular pattern of emitter tips has a 1 mm diameter with 50,000 tips on 4 μm centers. The height of each tip is approximately 1 μm and the gate aperture diameters are approximately 0.9 μm. These cathodes also rely on geometric field enhancement to enable operation at <100 V with the required electric fields. [12] The tip and gate material is Mo and the insulator material is SiO_2. The tips are fabricated in arrays as shown in Figure 5. Packing densities of cones of 10^9 tips/cm^2 [13] and current densities of 2000 A/cm^2 [14,15] have been demonstrated from small arrays of tips. There are significant performance variations between cathodes fabricated with the same process, however, 10 mA is routinely demonstrated at 100 V for FEA cathode configurations like the #1106E cathode with 50,000 tips. Gate electrode currents are routinely 1/1000 of the current emitted by the cathode.

Spindt-type cathode #1106E was conditioned for several days in a different UHV system at SRI International and then JPL before it was mounted to the In-FEEP thruster flange for integrated testing. It demonstrated 107 μA at 52 V with <1 μA through the gate electrode at 10^{-9} Torr at JPL. Spindt-type cathodes with this same configuration or similar configurations have been tested in various environments for applications including flat panel displays, sensors, amplifiers, and propulsion systems. [11, 16, 17] An SRI Int. cathode has even been flown in a spacecraft mass spectrometer.

While the Spindt-type cathode has demonstrated excellent efficiency, the performance of this cathode is very sensitive to the operating environment. Primarily oxygen environments change the surface work function and conductivity during cathode operation if the partial oxygen pressures are high enough. In primarily xenon environments, ions are formed between the tips and gate electrode which can sputter damage the sharp emitting tips to increase the tip radius of curvature and decrease the tip current [18]. While operating with thrusters using conductive propellants, there are concerns about the conductive propellant coating the insulating wall between the tips and gate electrodes to electrically short them together. The back flux of conductive material deposited on the cathode will increase with proximity to a beam target or vacuum chamber wall.

Diagnostics

An emissive probe was used in the experiments to measure the plasma potential in the ion beam. It was built at JPL with ceramic tubing and a tungsten filament which was 0.075 mm in diameter and approximately 4 mm in length. The probe electrical schematic employed is shown in Figure 2. Figure 6b shows the glowing emissive probe during its operation with the thruster. In our experiments the probe was mounted to an axial traverse feed-through. The probe could be positioned behind the beam target at 60 mm up to 3 mm from the ion extraction electrode.

The floating potential emissive probe technique was employed in the experiments. [19] Many V-I traces were obtained to determine the heater current levels required to ensure that the probe was floating at plasma potential and to determine the plasma potential. Once the required filament heater current was identified at both extremes in the plume-near the beam target and near the extraction electrode, the floating potential probe technique was employed to quickly measure the plasma potential as the axial position of the probe was varied. The voltage at the knees in the voltage-current curves was identified as the plasma potential. As this potential, further electron emission is significantly limited because of space-charge current limitations.

Facilities

An ultra high vacuum facility (UHV) was employed for the neutralizer experiments. The chamber pressure during these experiments was never better than 10^{-7} Torr, however, the facility and experimental apparatus were handled like UHV system components. The only non-metallic materials in the chamber were ceramics and teflon sleeves used for electrical insulation. An In foil beam target was used in this facility to minimize the contamination risk to the thruster emitter tip. This 20x20 cm^2 indium beam target was positioned ~6 cm from the beam. The center of the beam target had a ~2 cm opening in the center for the emissive probe to be traversed from behind the target up to the ion extraction electrode along the axis of the thruster.

The thruster and cathode common were electrically isolated from ground to determine the floating potential of the system as the ion and electron currents were varied. The electrical schematic is shown in Figure 2. A zener clamp was used to limit the floating potential of the thruster common to ±100 V w.r.t. ground; however, the floating potential of the thruster was limited to lower voltages because of limited electrical isolation in the data acquisition system (~0.5 MΩ).

Experimental Results

The In-FEEP thruster operated in current controlled mode at about 98 μA and 6200 Volts corresponding to a thrust of 10 μN. No arcing events between the tip and extraction electrode were observed during the experiments. 100 V biasing on the beam target with respect to ground was required to suppress secondary electron emission from the target. The target was biased in many of the experiments to minimize the influence of the secondary electrons on the measurements of the thruster floating potential and plasma potential. The experiments were conducted under sever time constraints. Therefore the duration of each of the 41 experiments was only a few minutes.

Thruster Charge Neutralization

Each of the cathodes was employed in demonstrations to neutralize the thruster charge. The floating potential of the thruster was observed as the neutralizer current was varied.

Thermionic Cathode

The results from the thruster charge neutralization demonstration with the thermionic cathode are shown in Figure 7. Unfortunately, the electron current collected by the cathode extraction electrode was not monitored. Data in Figure 9 do not show that the In-FEEP floating potential was zeroed by balancing the ion and electron currents, but it was reduced from approximately –70 V to –4 V by increasing the electron current to 99 μA with 98.4 μA of ion current. Additional cathode current was required to zero the thruster floating potential. This electron current, I_{ES}, as shown in Figure 8, was the total current from the cathode. Some of this current was intercepted by the gate electrode, therefore the cathode current which escaped the cathode was slightly lower. The electron extraction voltage in this experiment was ~6 V.

Figure 8 shows that the thruster floating potential could be zeroed with this cathode with additional cathode current. The thruster floating potential was 0.5 V with 98.4 μA of ion current and 100 μA of electron current. This data was collected in an experiment to evaluate the effect of electron energy on thruster floating potential. A floating potential of -3.4 V was demonstrated with 124 V applied between the cathode gate electrode and emitting surface and 99.4 μA of cathode current. These results show that the electron energy does not significantly impact the floating potential of the thruster and currents required for a thruster floating potential of ~0 V. However, the fraction of the cathode current collected by the electron extraction electrode probably decreased slightly with increased voltage.

Carbon Nanotube Cathode

The results from the thruster charge neutralization demonstration with the carbon nanotube cathode are shown in Figure 9. The performance of this cathode was not very stable. Also, the efficiency of this cathode was relatively low for a field emission cathode. Typically these cathodes are operated for several hours to stabilize their emission; however, there were severe time constraints during these experiments that prohibited the application of this conditioning procedure. Figure 9 shows that it was possible to attain a thruster floating potential of 0 V with the ion and carbon nanotube electron beams. However, the electron current required to achieve this potential with a 66 μA ion beam is uncertain. The electron source current presented in the graph was calculated by subtracting the cathode extraction current from the total cathode current. While the currents observed on the meters seemed to be balanced during the experiments, the current calculated from the values stored by the computer show that they were significantly different; the total cathode current was 836 μA, the gate current was 799 μA, and therefore the escaped current was 37 μA. These measurements should be repeated to determine the cathode current required to demonstrate a thruster floating potential of 0V with the carbon nanotube cathode. However, it is expected that balancing the escaping ion and electron currents will demonstrate a thruster floating potential of 0 V.

Spindt-Type Field Emission Array Cathode

The results from the thruster charge neutralization demonstration with the Spindt-type field emission cathode are shown in Figure 10. As the data shows, the performance of this cathode was remarkably stable in the relatively hostile vacuum environment. UHV environments are typically required to ensure stable operation of these cathodes. The current levels demonstrated were significantly lower (by approximately a factor of two) than the current demonstrated in UHV; however, the emission was fairly stable with a slight current increase during the experiments, as Figure 10 shows.

The efficiency of this cathode was excellent throughout the experiments despite the unconventional field emission cathode operating configuration. Field emission cathodes typically emit to a nearby anode. In these experiments, the cathodes were emitting to a low density plasma. It was expected that most of the emitted current would be collected by the gate current without an ion beam present, however, the majority of the current escaped from the cathode into the vacuum regardless of the ion beam current level. The beam current did affect the efficiency of the cathode. With an ion beam, the gate current was negligible. Without the ion beam 4 μA was collected by the gate electrode when the total cathode current was 66 μA.

Figure 11 shows the variation in thruster common floating potential with the difference between the ion and electron current emitted. Data from the experiments with the Spindt-type and thermionic cathode are included in this graph. The beam target was biased to 100 V above ground when these data were taken. This graph shows the sensitivity of the floating potential to the ion and electron current levels. The floating potentials were limited, as shown in Figure 11 because of ~0.5 MOhm path to ground in the data acquisition system.

Plasma Potential Measurements/Beam Neutralization

The plasma potential measurement and simulation results are shown in Figure 12 for several operating conditions with the beam target grounded in some cases and electrically biased to 100 V to suppress secondary electron emission in other cases. The numerical simulation [6] results were obtained for a 100 μA ion beam with 6200 V applied to the emitter tip with respect to the extraction electrode at 0 V and no neutralizer. The numerical and experimental results are in fairly good agreement. Discrepancies could be attributable to operating voltage variations. Virtual anodes were not detected in these measurements. It is possible to conclude from these measurements that the ion beam is not space-charge limited. However, at some operating points with the emissive probe < 5 mm from the ion extraction electrode, some of the emissive probe current was collected by the ion emitter tip. This current was interpreted as additional ion current by the ion source power supply. The power supply responded by decreasing the ion extraction voltage to maintain a constant current. Therefore, these measurements which affected the performance of the thruster with current reductions, are suspect and should be repeated with the thruster operating in a constant voltage mode. A much smaller emissive probe with a lower emission current should be employed in future measurements to provide better spatial resolution and less intrusive measurements.

Propulsion System Efficiency

A comparison of the efficiency of the propulsion system with each cathode is presented in Table 1. The thruster performance data compared were not all taken at the same thrust level, however, since the cathode performance decreases with current level, the power-to-thrust ratio would be even higher at the 7.6 μN thrust level investigated for the field emission cathode operating points. At 7.6 μN, the power-to-thrust ratio of the thruster with the field emission cathode is at least 50% lower than this ratio for the thruster operating with the thermionic cathode. Because the thermionic cathode power is fairly constant with increasing emission current, the performance advantage of the field emission cathodes over the thermionic cathode will not be as significant at higher current and thrust levels.

Conclusions

The experimental results presented in this article show that field emission cathodes can be used to neutralize the charge of an In-FEEP thruster. The demonstrations were performed in hostile conditions because of the chamber pressure and close proximity of the beam target. Despite this environment, these successful results were demonstrated. These results are significant because replacing thermionic cathodes with field emission cathodes improves the performance of the thruster and neutralizer system.

It was demonstrated that replacing a state-of-the-art thermionic cathode with a Spindt-type cathode can decrease the power-to-thrust ratio by 50% when operating at 10 μN thrust level. This result is particularly advantageous for the LISA mission, where 10 μN is the nominal thrust level required. Significant improvements to the power required by the propulsion system and the simpler operation of the field emission cathode also lead to simpler, smaller and lighter power processing units.

Plasma potential measurements validated theoretical results obtained previously. The results show that at 100 μA current levels, the neutralizer current affects the floating potential of the thruster but had minimal influence on the ion beam potential profile. These results suggest that the position of the electron beam relative to the ion beam is not important. These results coupled with the results from the thruster charge neutralization experiments suggest that one cathode could be operated with several thrusters operating at an electron current level equivalent to the total ion current.

Future experiments should focus on expanding our understanding of the results obtained during these experiments and improving on the experimental method. Longer duration experiments should be performed to determine if the results from these experiments are representative of the results that would be characteristic of steady-state operation. Better electrical isolation between the thruster and ground should be established in future experiments to determine the true thruster floating potential when operating without a neutralizer. These experiments should be repeated at much higher current levels to determine how the results obtained are affected by the ion current level up to the maximum of ~800 μA from these ion sources. The electron extraction electrode current should be recorded also. The experiments should be performed in larger vacuum facilities to mitigate the influence of the test chamber on the experimental results. The thruster should be operated in voltage controlled mode during the plasma potential measurements. And finally, the performance of this thruster, over its full current range, should be characterized on a thrust stand with a neutralizer to determine if space-charge neutralization is required at higher current levels.

Acknowledgements

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TABLE

Table 1. In-FEEP thruster performance comparison with three different neutralizers.

Cathode	P_{ISH} (W)	P_{ISG} (W)	P_{ESG} (W)	P_{ESH} (W)	P_D (W)	P_Σ (W)	T (µN)	P_Σ/T (W/µN)
Thales-Thompson-Thermionic	0.4 (0.04 A 10V)	0.002 (0.53 µA 6262 V)	?	1.575 (0.25A 6.3V)	0.75 (98 µA 6268V)	2.727	12.0	0.227
FEPET C arbon-nanotube Field emission	0.4 (0.04A1 0V)	0.003 (0.49 µA 5993V)	0.4 (0.793 mA 510 V)	0	0.429 (66 µA 6503 V)	1.23	7.9	0.156
SRI Int. Spindt-type Field emission	0.4 (0.04 A 10V)	0.001	5.4×10^{-6} 0.1 µA 54 V	0	0.373 (66 µA 5652 V)	0.774	7.6	0.102

FIGURES

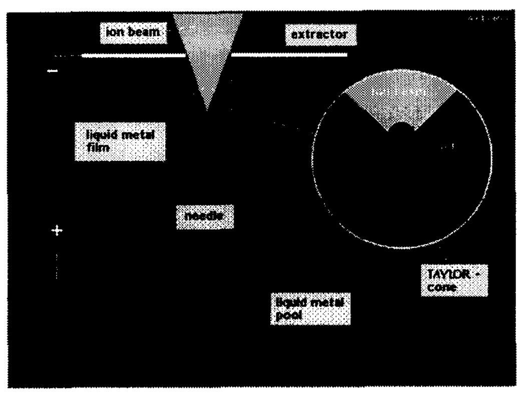


Figure 1. In-FEEP emitter configuration.

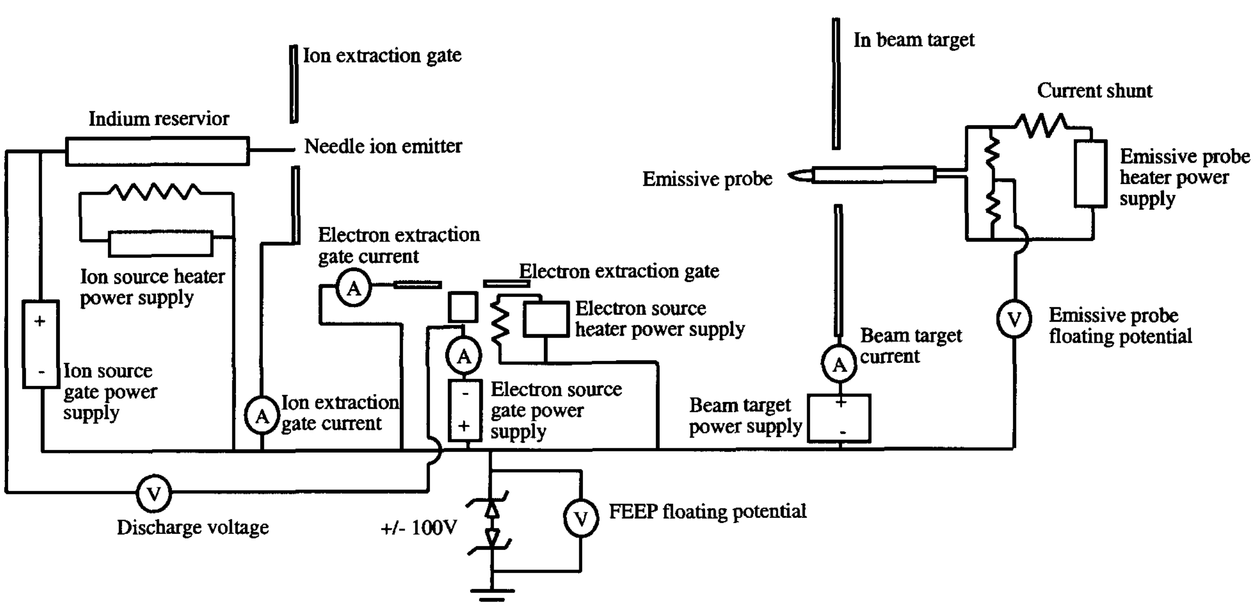
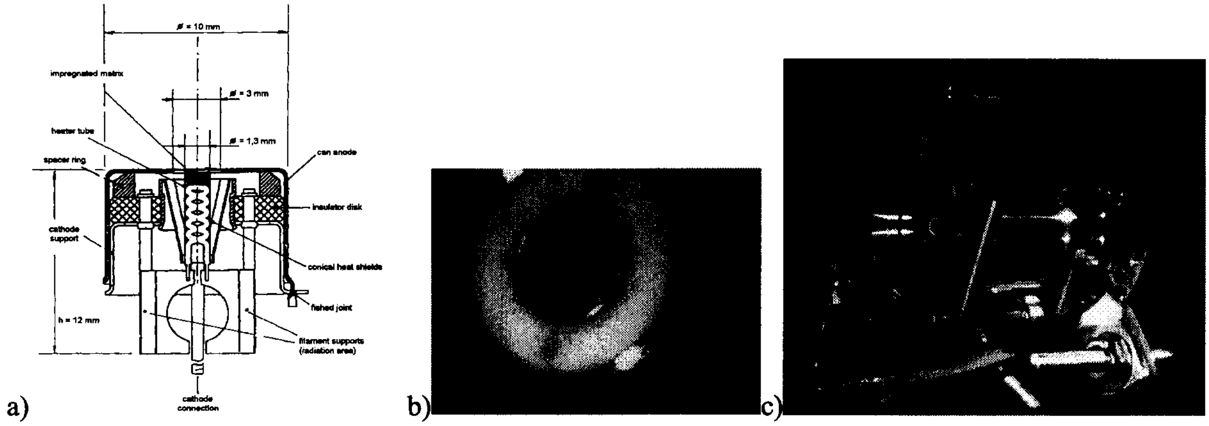
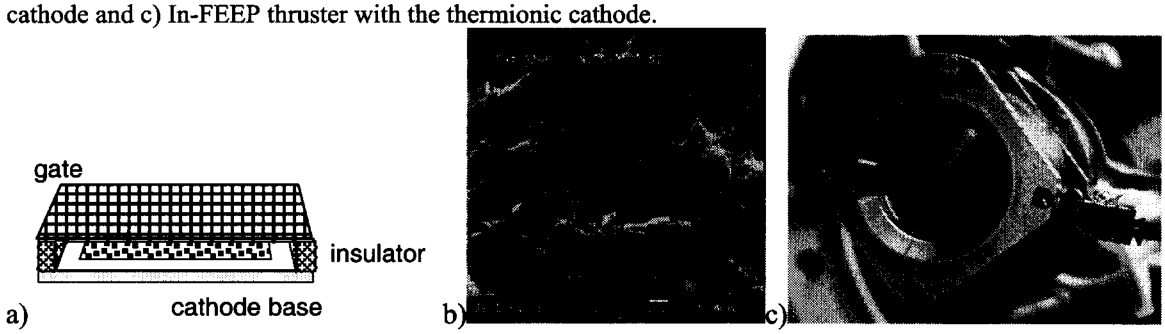


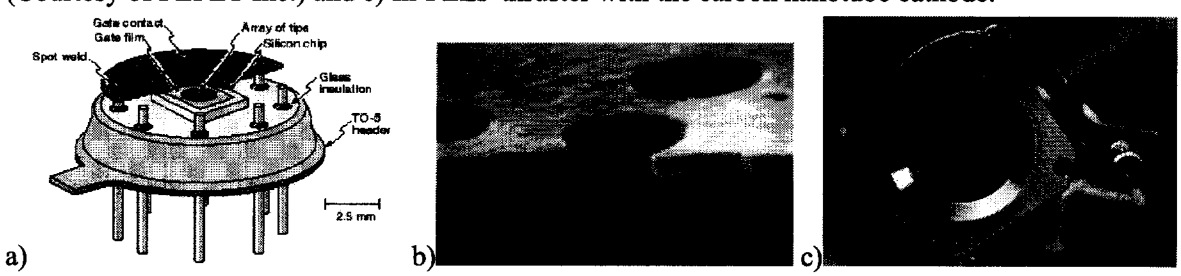
Figure 2. Electrical schematic employed in the neutralizer characterization experiments.



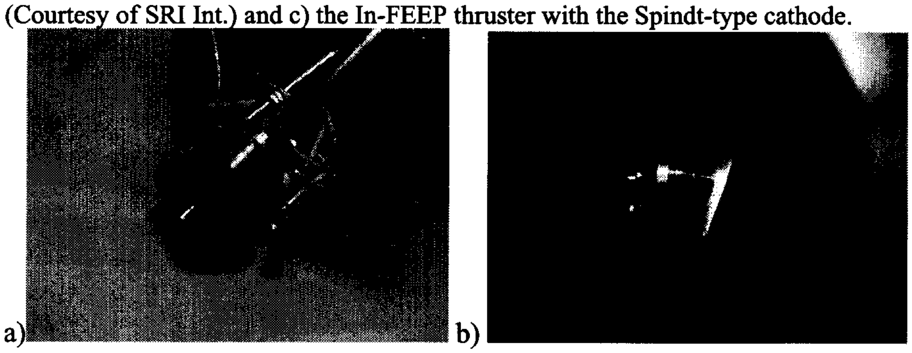
a) b) c)
Figure 3 a) Configuration of M-44 Thales-Thompson Thermionic cathode (Courtesy of ARCS), b) the thermionic cathode and c) In-FEEP thruster with the thermionic cathode.



a) b) c)
Figure 4. a) Configuration of a FEPET carbon nanotube field emission cathode b) carbon nanotubes (Courtesy of FEPET Inc.) and c) In-FEEP thruster with the carbon nanotube cathode.



a) b) c)
Figure 5. a) SRI International Spindt-type cathode configuration (Courtesy of SRI Int.), b) cone and gate structure (Courtesy of SRI Int.) and c) the In-FEEP thruster with the Spindt-type cathode.



a) b)
Figure 6. a) In-FEEP thruster with the SRI International Spindt-type field emission cathode on an 8-inch flange, b) In-FEEP thruster, thermionic cathode, and emissive probe all operating in the vacuum system during plasma potential measurements.

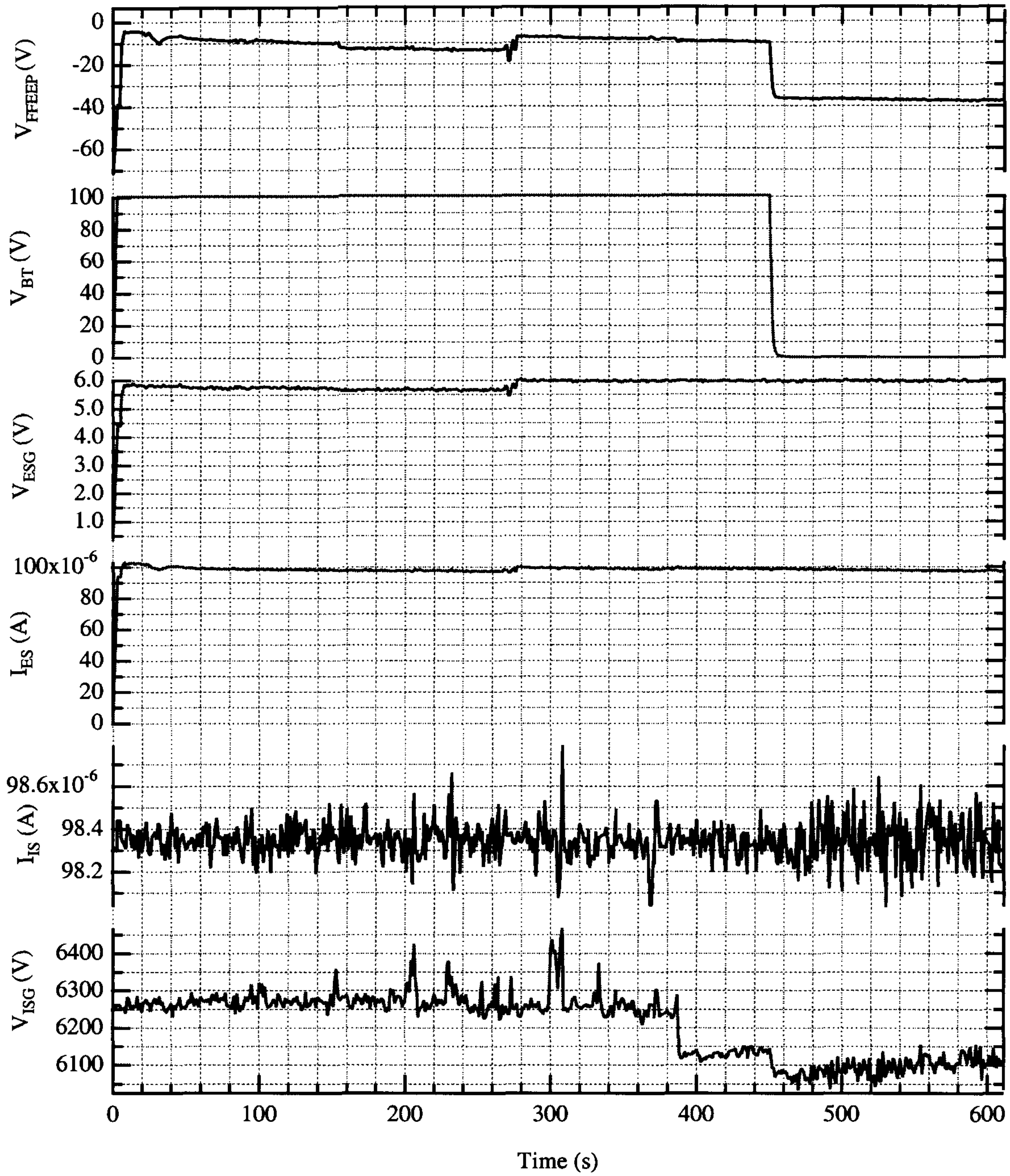


Figure 7. Data showing the thruster and thermionic cathode performance and the thruster floating potential.

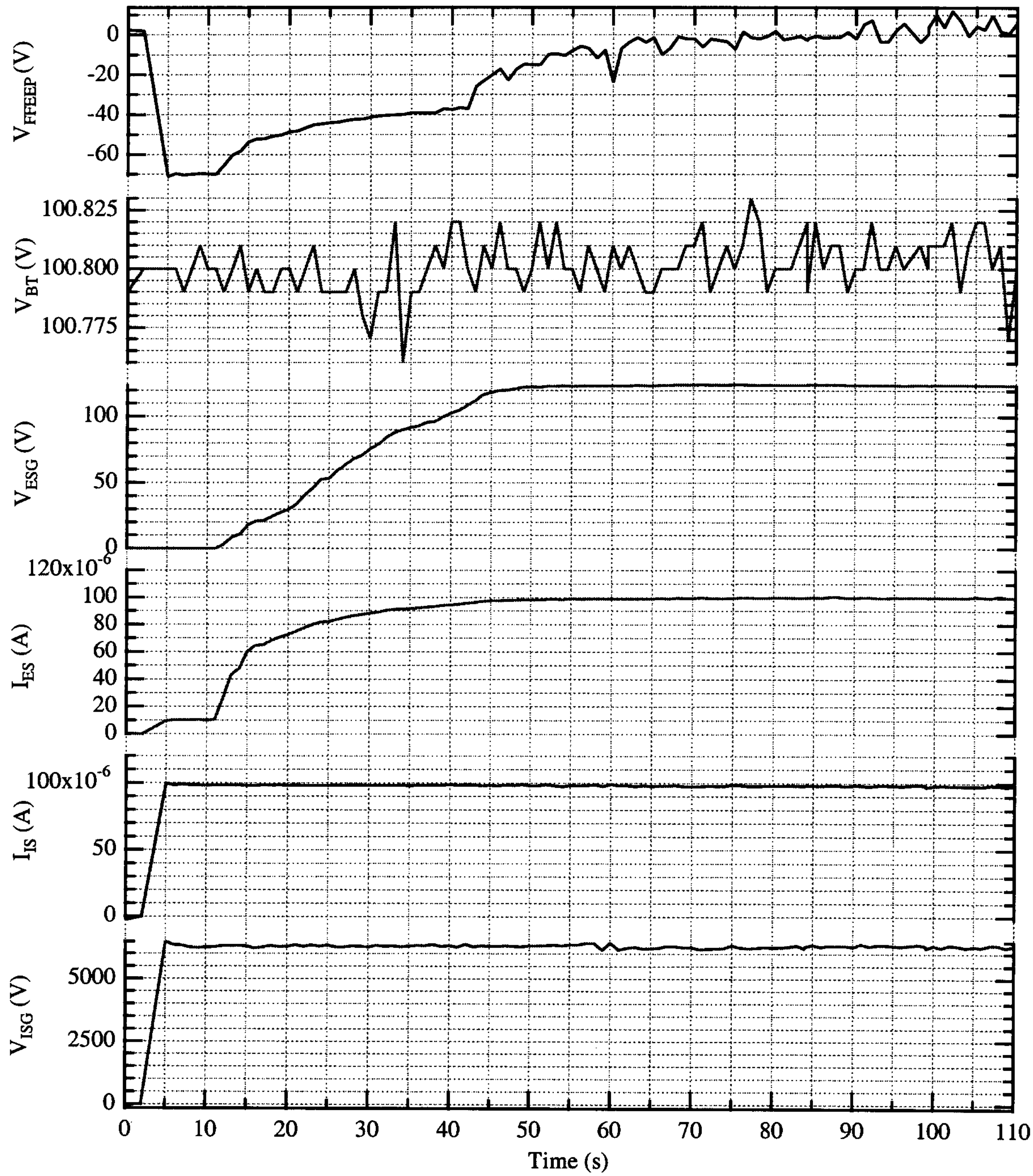


Figure 8. Data showing the effect of thermionic cathode voltage and current on thruster floating potential.

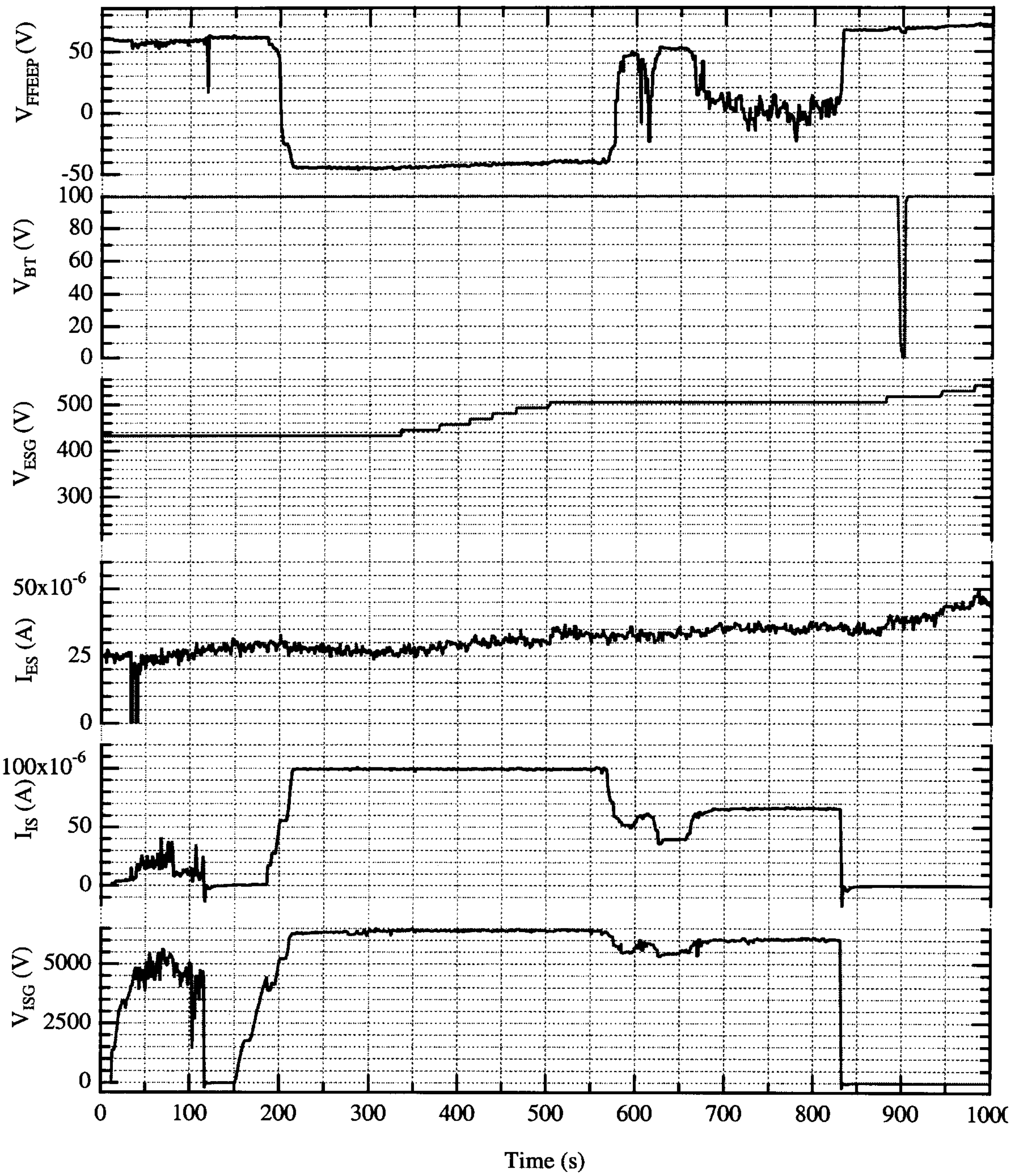


Figure 9. Data showing the effect of a carbon nanotube cathode current on thruster floating potential.

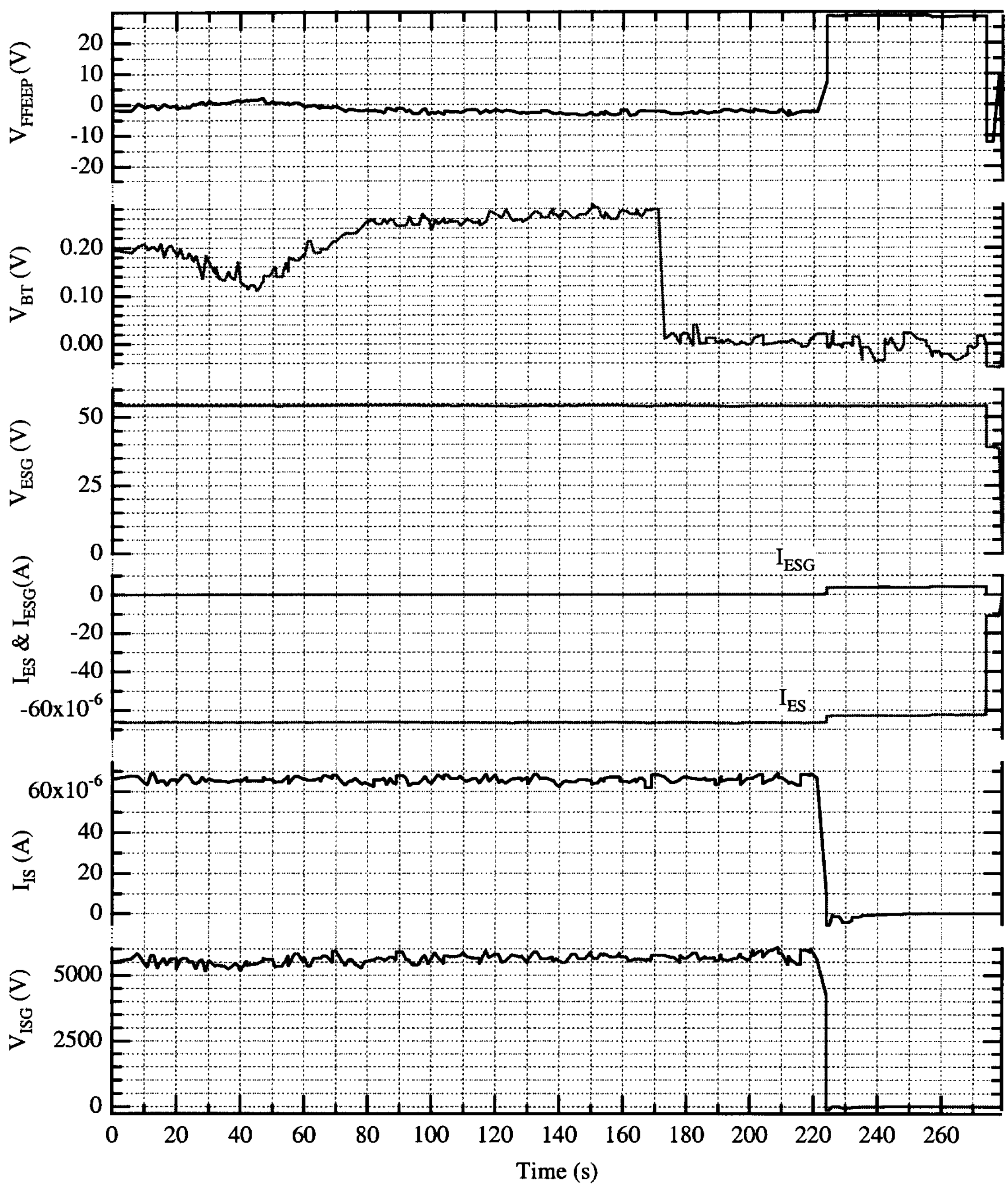


Figure 10. Data showing thruster charge neutralization with a Spindt-type field emission cathode.

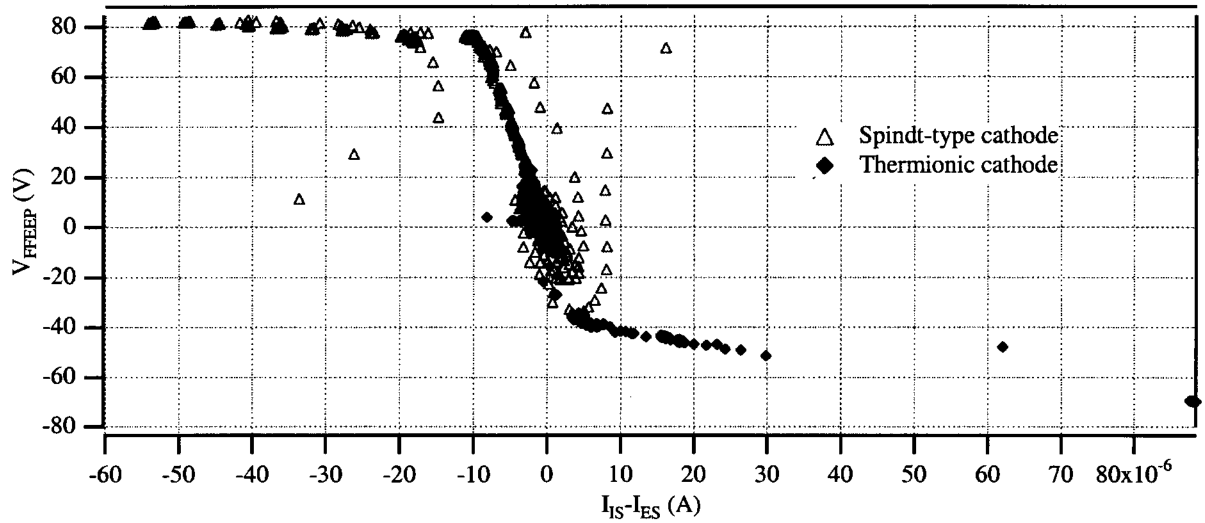


Figure 11. Thruster common floating potential variations with difference between ion and electron currents with beam target biased at 100 V above ground.

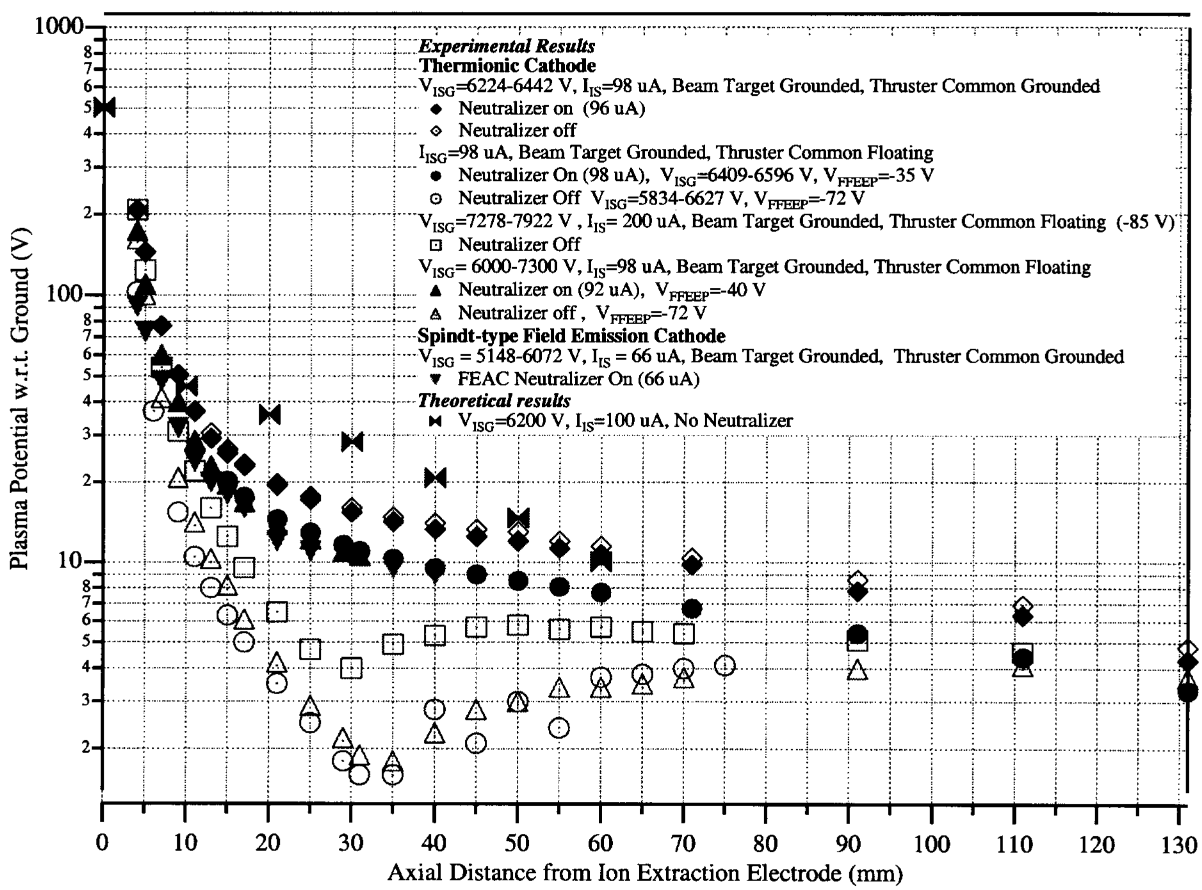


Figure 12. Theoretically and experimentally determined plasma potentials in the In-FEEP thruster plume with the operating parameters defined in the legend.

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