Development and Testing of a Field-Emission Neutraliser for Micro-Electric Propulsion

IEPC-2007-171

Pierre-Etienne Frigot*
AOES B.V., Haagse Schouwweg 6G, 2332 KG Leiden, The Netherlands

Karen L. Aplin†, Barry J. Kent
Rutherford Appleton Laboratory, Oxfordshire OX11 0QX, United Kingdom

and

Davide Nicolini§, José Antonio Gonzalez del Amo**
European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

Abstract: The work reported was carried out through a European Space Agency contract in the frame of LISA/Pathfinder with the Rutherford Appleton laboratory for the design, development and manufacturing of a field-emission neutralizer intended for use with micro-electric propulsion systems. The fabrication process is briefly described and the device characteristics for a neutralizer are outlined. Results from experimental activities performed at ESA are presented. The neutralizer assembly has been operated for short period of time in constant-current mode at levels ranging from 100µA to 1mA with accuracy better than 0.1%. A predicted power consumption of 0.2 W/mA has been verified. Unstable behavior of the emission properties over time has been observed. Temperature sensitivity has been identified and characterized, although it was found not to be the cause of those instabilities.

Nomenclature

I	=	current
V	=	voltage
E	=	electric field
Φ	=	work function
β	=	field enhancement factor
d	=	distance

* Consultant Engineer, ESA Mechanical Engineering Department, pierre-etienne.frigot@aoes.com
† Space Science and Technology Department, K.L.Aplin@rl.ac.uk
§ LISA Pathfinder and Microscope projects, ESA Scientific Projects Department, Davide.Nicolini@esa.int
** Head of Electric Propulsion Section, ESA Mechanical Engineering Department, Jose.Gonzalez.del.Amo@esa.int

I. Introduction

The cathode is a critical component of any electric propulsion subsystem: the source of electrons is used for sustaining the plasma source of the thruster and/or balancing the electric charge of the spacecraft.

For propulsion systems with mN to N thrust force capability, hollow cathode technology is typically used at high current levels (100mA-10A), via gas discharge. For ignition of the gas discharge, a thermionic cathode[1] with low work function surface is used, which generates electrons when heated up to high temperature (typ. 1300K with Barium oxides impregnated cathode). Hollow cathode technology suffers from well-known lifetime issues due to the ion bombardment of the materials by the discharge and thermal stress provoked by ignition cycling. The thermo-ionic cathode itself is very sensitive to contamination by oxygen and requires proper handling and conditioning sequences. At low current levels (1mA-10mA) required for micro-propulsion systems (µN), a single thermionic cathode is used as a source of electrons. Thermal stress remains a lifetime issue and a warm-up time is required thus preventing instantaneous ignition. For micro-electric propulsion systems[2] (Field Emission Electric Propulsion, colloids, etc), thermionic neutralizers are baseline. However it should be clear from the summary above that thermionic technologies are not ideal, particularly as the cathode is a single cause failure source for the propulsion system. This has motivated the research and development of unheated cathode neutralizers over the world. The main improvement from this technology is the reduction of the number of single cause failures for the cathode (thermal stress which can damage insulation, poisoning of the insert, etc). The response time of the propulsion subsystem is improved as the non-heated cathode can be turned on instantaneously.

There are two non-heated cathode technologies: the field-emission technology and the plasma-bridge technology. The latest technology is not adequate to micro-electric propulsion systems as the power requirement for sustaining the plasma source would be higher than for heating a thermionic insert. Field-emitters can be subdivided in two categories depending if the Spindt-type tips or the carbon nano-tubes (CNT) are used. Silicon tips field-emitters have been available for many years and many organizations have published studies on their particular manufacture route and device performance. They were selected as an appropriately mature technology for the field-emission (FE) neutralizer developed at the Rutherford Appleton Laboratory (RAL) between 2002 and 2004, under contract with the European Space Agency (ESA) for the LISA-Pathfinder mission[3].

The RAL neutralizer has been tested twice since it was delivered to ESA. Both test campaigns took place at ESTEC, in the tests facilities of the ESA Propulsion Laboratory, in August 2005 and May 2007. Whereas the first test campaign objective was the functional characterization of the neutralizer for acceptance after delivery to ESA, the second one aimed to investigate the temperature sensitivity.

The ESA Propulsion Laboratory is providing test services and technical consultancy in support to ESA projects from the early phase of technology development to the acceptance of flight hardware. EPL is ISO certified laboratory with extensive experience in electric propulsion technologies, and numerous collaborations with European and international laboratories

II. Field Emission neutralizer

The neutralizer assembly (NA) is composed of two printed circuit boards (PCB) housed in an aluminum-alloy structure. The neutralizer assembly is cold-redundant and a single PCB contains 66 silicon dies; each containing 20 arrays of Spindt-type tips (Fig. 1).

The production of the dies is based on normal semi-conductors processes (lithography, PECVD, direct sputtering…). Optimization of the fabrication process[3] and strict selection criteria based on probe tests of each dies, have allowed obtaining reliable field-emitter arrays with 5,800H lifetime demonstrated. The NA includes an integrated heater and temperature sensor (PT1000) for bake-out and temperature monitoring. The operational specifications of the neutralizer assembly are summarized in Table 1.

The device tested at ESA was not fully wired and a maximum current of 1mA at 200V gate voltage was predicted.

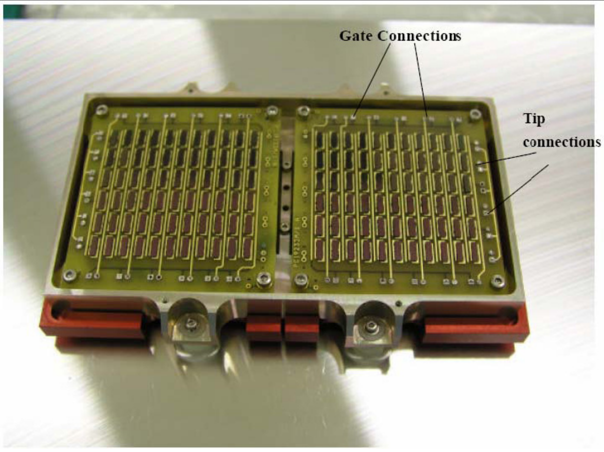

Figure 1. RAL neutralizer assembly

Table 1. RAL neutralizer assembly functional and dimensional specifications

Parameter	Value	Unit
Emitted current	0 – 6	mA
Total supplied current (max)	7.2	mA
Current lost to gate (max)	1.2	mA
Gate voltage (max)	200	V
Emitter power	1.44	W
Power consumption	0.2	mA/W
Heater power (nom)	4.5	W
Lifetime	> 6000	hours
Cycles	> 500	
Mass (excl. cable harness)	87	g
Envelope diameter	106	mm
Height	20.5	mm

III. Experiment

The experimental activities on the RAL neutralizer assembly were carried out under high-vacuum conditions (<10^{-6}mbar) in the test facilities VC#1 and VC#6 of EPL. Thermal washers inserted between the base-plate and the neutralizer provided insulation with respect to the vacuum facilities. The voltages and currents were set and monitored with commercial power supplies and ammeters. FUG power supplies and Keithley 2000 ammeters were interfaced to a National Instruments SCXI-1052 data acquisition system (DAQ). A copper plate collector raised at a 300V potential was facing the active area of the neutralizer at ~1cm distance. The signal of the internal temperature sensor of the neutralizer, and the vacuum level in the test facility were read by the same DAQ. Dedicated software was programmed under Labview™ for operating the instruments and logging the data continuously. In constant-current mode operation, a software loop controlled the gate voltage (0.1V resolution) to keep the collector current constant. For regulating the temperature of the NA, a software loop controlled the internal heater voltage to keep the neutralizer temperature constant. The DAQ was run at 1Hz frequency. A simplified schematic of the test setup is shown in Fig. 2.

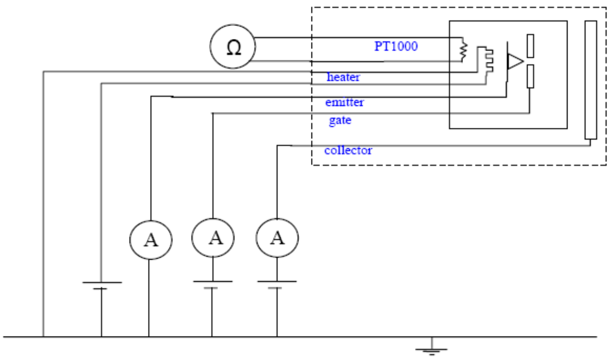

Figure 2. Test setup schematic

IV. Results and Discussion

After the neutralizer is exposed to atmospheric pressure, bake-out and conditioning must be performed before operation. The bake-out sequence aims to reduce the amount of surface impurities which could reduce field-emission process, and to minimize the risk of accelerated degradation of the device due to sputtering of electron-induced ions which would be increased by high out-gassing. Conditioning was done by applying voltage ramps up to a "safe" value (below emission threshold), and successively returning to 0 and increasing the "safe" value until emission is detected.

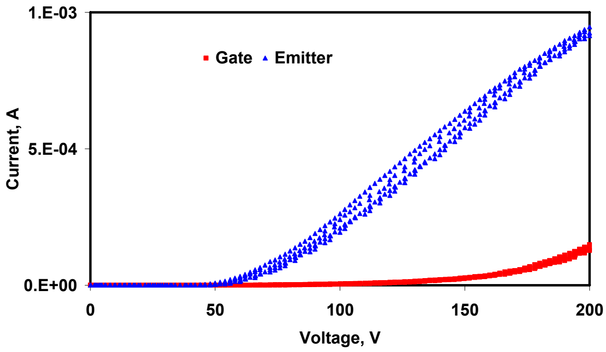

Figure 3. I-V plot; V_C=300V

Full characterization of the emission properties was performed by raising the gate voltage up to 200V which allowed obtaining an emitter current up to ~1mA (Fig. 3), as predicted, for a power consumption of 0.2W/mA. Despite the repeated conditioning sequence, hysteresis behavior remained during the all experiments. The high value of gate current was attributed to limiting space-charge effect which was reduced by increasing the collector voltage up to 400V (fig.4(a)). Less than 5% of the total emitted electronic current was flowing to the gate then. Fowler-Nordheim (FN) theory[6] describes the non-linear relation between the emitted current I ($A.cm^{-2}$) and the local electric field E ($V.m^{-1}$):

$$I \propto \frac{K \cdot E^2}{\Phi} \exp\left(-\frac{B \cdot \Phi^{3/2}}{E} \right) \qquad (1)$$

where B = 6.83 x 10^9 $V.eV^{-3/2}.m^{-1}$, K is a constant, and Φ is the work function of the materials. The local electric field E is related to the gate voltage V_G as $E = \beta V_G/d$, where β is the field enhancement factor and d is the distance between the emitter and the gate. The FN plot $\ln(I/V^2)$ versus (1/V) can be approximated to a straight line which slope k can be expressed as:

$$k = -\frac{B \cdot \Phi^{3/2} \cdot d}{\beta} \qquad (2)$$

Figure 4(b) shows the FN plot corresponding to the data presented in Fig. 4(a): field-emission process is verified and extrapolation of the FN plot could allow predicting the maximum current achievable at higher voltage (although not convenient in space application).

Short endurance testing of the neutralizer was performed in constant-voltage (CV) and constant-current (CI) modes from 100µA to 1mA. Both modes revealed unstable emission properties of the neutralizer over time, and especially in the low frequency range. Figure 5(a) shows the behavior of the gate voltage in CI mode at I_C=200µA over 3 hours: the collector current is regulated at a mean average of 203µA with a standard deviation less than 3% of the mean, while the gate voltage varies between 100 and 120V. In CV mode, the current usually dropped over time (1 hour) after reaching a maximum value at start. Similar unstable behavior on that technology was previously reported[5] and was correlated with room temperature variation (resulting in 20% current variations in CV mode). Little post-processing of the temperature signal allows determining a clear correlation between the

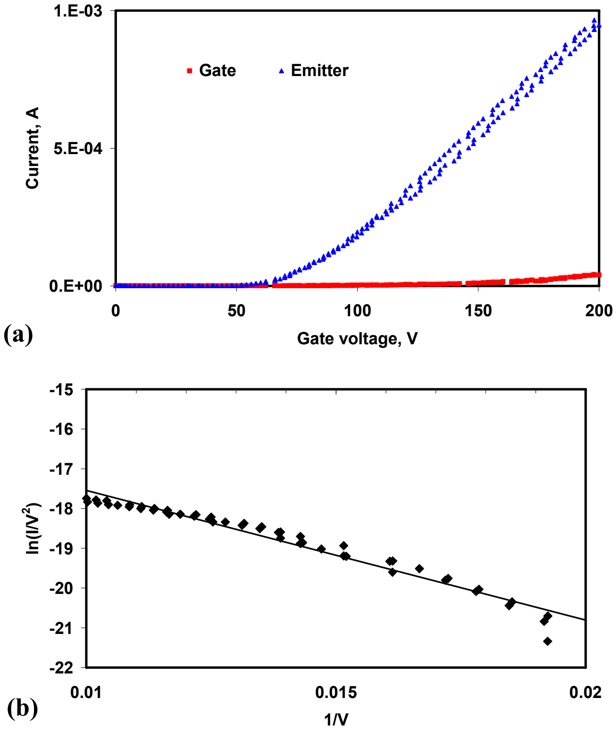

Figure 4. (a) I-V plot (b) FN plot; V_C=400V

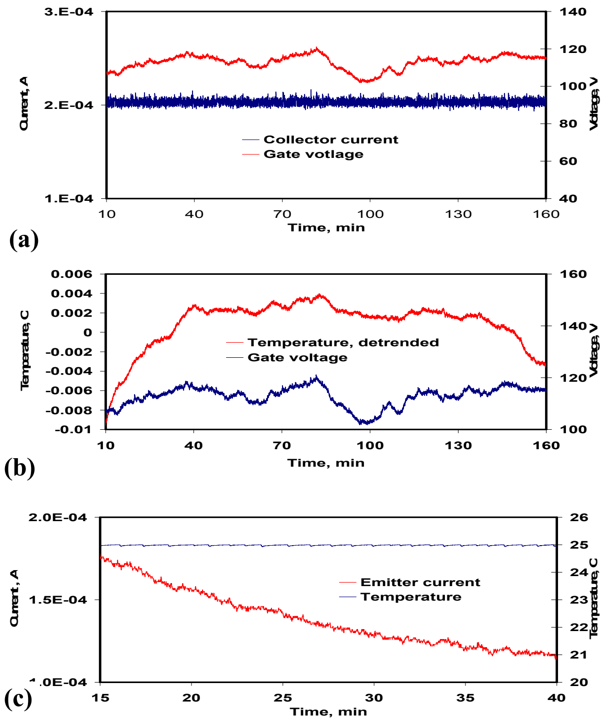

Figure 5. (a) (b) Endurance test in CI mode; I_C=200µA (c) Endurance test in CV mode; V_G=100V

temperature and the gate voltage (Fig. 5(b)).

In a first attempt to determine if the neutralizer is effectively temperature-sensitive, experiments were performed in CV mode at regulated temperature. Figure 5(c) shows the behavior of the emitter current in CV mode with V_G=100V over 1 hour: despite regulation of the temperature at a mean average of 24.98C with a standard deviation less than 0.05% of the mean, the emitter current decreased from 230 to 110µA; emission performances were recovered at start of the next test indicating that there was no permanent degradation.

Because the temperature sensor provides a unique reference measurement for the neutralizer assembly, there is some uncertainty in the local temperature of the silicon tips. However, it is reasonable to assume that the mean value of the temperature distribution of the tips follows the temperature measured by the sensor. Therefore, additional experiments were performed to refine the temperature sensitivity investigation: in a safe approach, temperature of the neutralizer was operated successively at 23, 25 and 29C regulated temperature with accuracy better than 0.1C. Measurements (Fig. 6(a)) revealed that the emission properties of the neutralizer tend to increase along with temperature. Work performed in the field of semi-conductors electronics and vacuum technologies pointed out the dependence of the field-emission process with respect to temperature[6-7]. According to Eq. (2), and assuming a constant field enhancement factor β, the trend of the work function Φ should be revealed by the trend of the FN plots' slopes. The FN plots (Fig. 6(b)) suggest that the work function Φ decreases along with temperature. Previous works identified thermal-assisted field-emission process characterized by lower onset field and stiffer I-V plots due to the substantial reduction in the work function of the materials when temperature is increased. Furthermore, n-type semi-conductors are characterized by a Fermi level E_F closer to the conduction band level E_C than the donors level E_V; this property is even more pronounced when temperature increases and consequently, the work function Φ is reduced. The measurements reported in this paper have not been repeated thus statistical analysis is not possible. But, in agreement with literature and materials sciences theory, first set of measurement suggest that the neutralizer is sensitive to temperature, with variation of several degrees (at temperature reference point) causing the emitted current to vary of several tens of microampere (µA). Consequently, since a voltage sensitivity of ~5-10µA/V can be derived from the characterization of the neutralizer, the variations of the gate voltage for the neutralizer operated in CI mode due to thermal changes can be estimated roughly to ~1V/K.

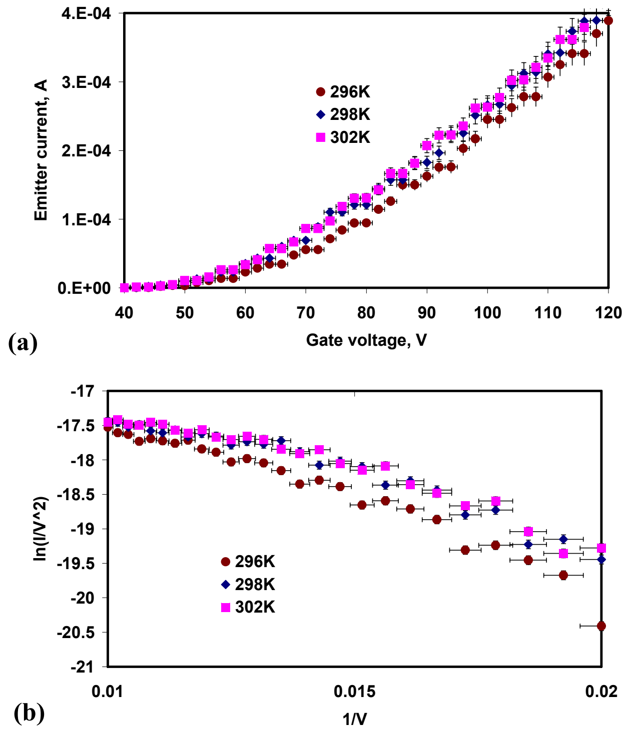

Figure 6. (a) I-V plots at various neutralizer regulated temperatures (b) Corresponding FN plots; V_C=200V
Hysteresis is not shown for better readability of the data; Error bars are based on conservative estimations of the measurement instruments' accuracies

The physical processes which could potentially induce thermal changes of the individual tips during field emission have been listed in the frame of a failure mechanisms analysis[4]: Joule effect, Nottingham effect and ion bombardment should all induce heating of the tips. Hence, if the temperature sensitivity of the neutralizer was the principal cause of the observed variations, the emission properties of the neutralizer should improve at the beginning of neutralizer operation and stabilize once thermal equilibrium is achieved. On one hand, such behavior is not observed from measurements taken in CV and CI modes (Fig. 5), and, on the other hand, variations in emitter current or in gate voltage are far higher (x10^3) than the estimated ones for the recorded temperature variations. Therefore, thermal changes don't appear to be the main cause of disturbance of the emission properties of the neutralizer. Instead, it is believed the unstable behavior of the neutralizer is intrinsic to the field-emitter technology. If operated in CI mode, the instabilities don't have any impact on the functional parameters of the neutralizer. But at system level, it shall imply an appropriate design of power electronics with enough margins on the gate voltage control range.

V. Conclusion

The RAL neutralizer assembly has been tested at the ESA Propulsion Laboratory and its performances have been characterized. Power consumption is decreased significantly compared to thermionic neutralizers as there is no heater operation during emission. Field-emitters have initially been identified to be used as neutralizers in micro-electric propulsion systems (<150μN), but CNT with higher current density capability could make field emission a promising candidate neutralizer technology for mini-electric propulsion systems (<1mN) or other advanced propulsion concept[10].

References

[1] Shih A., "High Emission Density Thermionic Cathode", Cathode for Relativistic Electron Beams Workshop, 2001

[2] Nicolini, D., "MicroNewton Propulsion Subsystem Development for Drag-Free Spacecraft", *4th International Space Propulsion Conference*, 2004

[3] B. J. Kent et al, "A field effect spacecraft neutralizer for the LISA Pathfinder mission", Class. Quantum Grav., 22, 2005

[4] K.L. Aplin, C. M. Collingwood and B. J.Kent, "Reliability tests of gated silicon field emitters for use in space", J. Physics D: Appl. Physics 37 2009-17, 2004

[5] K.L. Aplin et al, "Variability in long-duration operation of silicon tip field emission devices", J. Vac. Sci. Technol. B 24(2), 2006

[6] L. Liao et al, "Investigation of the temperature dependence of the field emission of ZnO nanorods", Nanotechnology 18, 2007

[7] H. Nakane, J.P. Dupin and V. T. Binh, "Emission characteristics of ultrathin layer solid-state emitters, temperature, and thickness dependence", J. Vac. Sci. Technol. B 21(4), 2003

[8] S. Weis, K.H. Schartner, H. Lob and D. Feili, "Development of a capacitively coupled insert-free RF-neutraliser", *29th Electric Propulsion Conference*, 2005

[9] P.D. Reader, D.P. White, G.C. Isaacson, "Argon plasma bridge neutralizer operation with a 10-cm-beam-diameter ion etching source", J. Vac. Sci. Technol. 15(3), 1978

[10] R. Hoyt and R. Forward, "Performance of the Terminator Tether for Autonomous Deorbit of LEO Spacecraft", *35th Joint Propulsion Conference*, 1999