Experimental Study of the Neutralization Process in Field-Emission Electric Propulsion

IEPC-2009-032

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

Pierre-Etienne Frigot[*], Alexandra Bulit[†], Davide Nicolini[‡], José A. Gonzalez del Amo[§]
European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

and

Marco Capacci[**]
Thales Alenia Space Italia, Florence Site, 50013 Campi Bizencio, Italy

Abstract: Results of an experimental test campaign dealing with the neutralization on FEEP technology are reported together with simulations of the thermionic neutralizer chosen for the MICROSCOPE and LISA-Pathfinder missions. Stabilization of the floating potential is obtained instantaneously predicting a moderate charging of the spacecraft in a range of a hundred of Volts. Ion induced secondary electron emission negligible influence on neutralization process is demonstrated. Plasma parameters inside the vacuum chamber are roughly extrapolated from neutralizer performances and correlated with thruster propellant.

Nomenclature

δ	=	secondary electron emission yield
I	=	current
λ_D	=	Debye length
V	=	voltage
k	=	Boltzmann constant
ε_0	=	vacuum permittivity
N_e	=	electron density
T_e	=	electron temperature
n_{In}	=	indium neutrals density
n_{In}^{+}	=	indium ions density
σ	=	collision cross-section
q	=	elementary charge
r	=	distance

[*] Electric Propulsion Engineer, ESA Mechanical Engineering Department, PierreEtienne.Frigot@esa.int
[†] Electric Propulsion Engineer, ESA Mechanical Engineering Department, Alexandra.Bulit@esa.int
[‡] 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
[**] Thales Alenia Space Italia, Florence Site, Marco.Capacci@thalesaleniaspace.com

I.Introduction

Field emission electric propulsion (FEEP) is being developed in the frame of the LISA-Pathfinder and Microscope missions[1]. It presents unique features of thrust controllability in the micro-Newton range and low-noise actuator inherent to electric propulsion technologies without moving parts. Several research activities were carried out by the ESA propulsion laboratory during the early development phase in the 80' and the laboratory is still providing support to the industry for specific verification test of the FEEP technology.

FEEP thrusters are based on the physical process of field ionization of an alkali metal in liquid phase immersed in an electric field generally produced between an electrode and the liquid metal itself raised at different potentials. First, the liquid metal reacts to the electric field by forming microscopic structures referred as Taylor cones with tip radius typically in the order of 10-100 nm. Such tip geometry creates a local enhancement of the electric field which allows reaching high electric field (10^7 V/m) necessary for field ionization. Ions are extracted from the bulk of the liquid metal – commonly referred as the emitter – and subsequently accelerated toward the electrode – commonly referred as the accelerator – before leaving the thruster. Various geometries of emitter are shown in Fig.1.

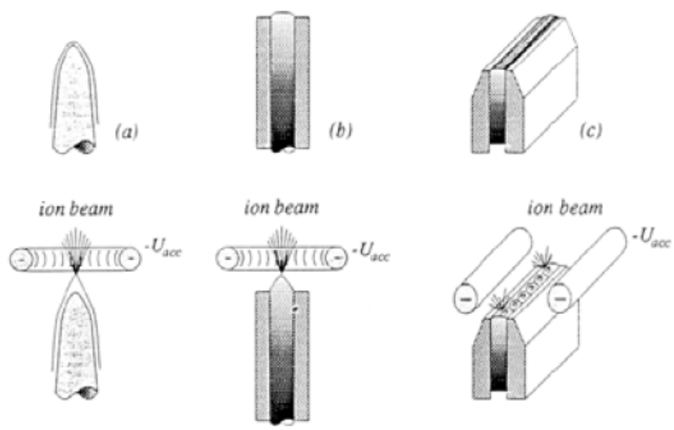

Figure 1. Different emitter geometries: needle (a), capillary (b), and slit (c)

As any electric propulsion system, the FEEP thruster is completed by a neutralizer assembly whose function is to balance the electric charge of the spacecraft by expelling as many electrons as ions exhausted by the thrusters (see Fig.2a). The neutralization concept on both LISA-Pathfinder and Microscope is based on the auto-regulation of the potential of the spacecraft with respect to the potential of the surrounding plasma for allowing sufficient extraction of electrons from the neutralizer. Indeed, the neutralizer is a diode with an acceleration-deceleration electrical scheme between two electrodes where the anode extracts the electrons from a thermionic cathode (see Fig.2b). The critical parameter of such a design is the existence of an external electric field to extract the electrons outside the neutralizer and to overcome space-charge barrier which would limit the current and reflect the electrons toward the neutralizer. Therefore, it is predicted that there will always be a potential difference between spacecraft and surrounding plasma when FEEP system is in operation. Demonstration of the neutralizer emission capability immersed in plasma environment was performed successfully[2].

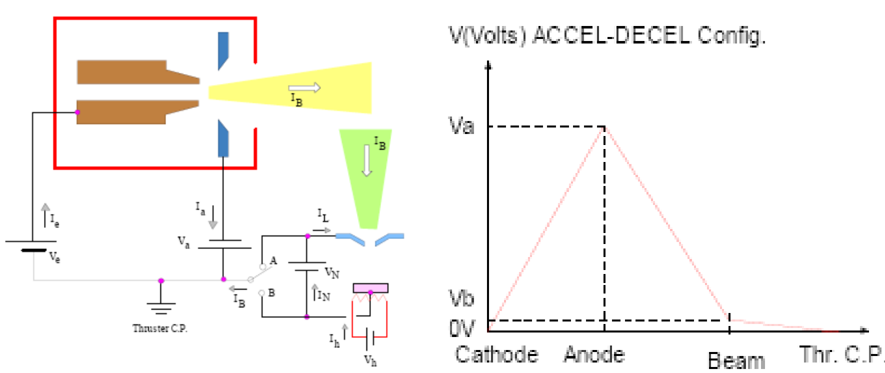

Figure 2. (a) Neutralizer functional scheme and (b) voltage potential distribution

The neutralizer assembly has been developed by Thales-Alenia Space Italy first in the frame of Microscope FEEP propulsion system development activities funded by ESA. The neutralizer is currently under lifetime testing as the last step of the qualification activities and the activities are in manufacturing phase of the flight model for LISA-Pathfinder[3].

The ESA propulsion laboratory (EPL)[4] was requested to perform an investigation of the neutralization process of a representative FEEP system with the objective to confirm experimentally the auto-regulation concept of the neutralizer.

II.Experimental apparatus

The Gigant test facility of the ESA propulsion laboratory was selected for this testing activity (see Fig.3(a)). It was used previously for the lifetime test of the EADS-Space Transportation GmbH RIT-10 in the 90'. The vacuum chamber is composed of a small 40 cm diameter vessel used for thruster integration – the hatch – and a large 1.6m diameter vessel for firing operation – the main chamber. The vessels are connected together by a gate-valve. Such a configuration is standard on EPL test facilities for allowing either a quick access to the thruster while keeping the main chamber in vacuum, or to the main chamber while keeping the thruster in vacuum conditions in the hatch. The pumping system is composed of typical high-vacuum pumps such as rotary pump, roots-blower and turbo-molecular pump. The final pumping stage is based on cryogenic pumps and cold-heads. Both the hatch and the main chamber have independent pumping systems. Moreover, Gigant is equipped with a beam target specially designed for reducing back-sputtering created by the impingement of the ions on the walls of the main chamber (see Fig.3(b)), a bake-out system to accelerate the out-gassing process during the start of the vacuum sequence. Vacuum gauges are installed on both the hatch and the main chamber. A control system allowed an automatic vacuum sequence from atmospheric pressure.

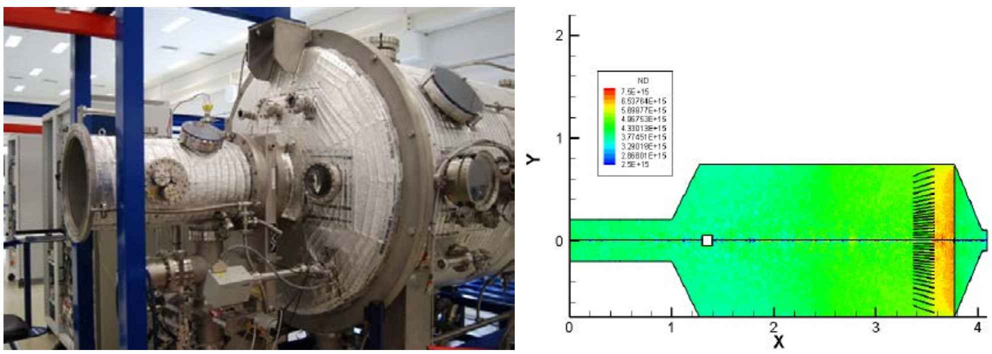

Figure 3. EPL vacuum chamber #3 (Gigant) (a) photography and (b) back-sputtering simulation

The thruster was an Indium ion source procured at the Austrian Research Center with beam current capability roughly between 10-100 µA (equivalent to 1 and 10 µN thrust at 6 kV beam voltage). The emitter was a capillary type as shown in Fig.4(b). Two high-voltage power supplies were needed to create the electric field necessary for field ionization and a high-current power supply was used to activate the heaters for melting the Indium (solid at room temperature). The neutralizer was an engineering model built by TAS-I for the Microscope program with a maximum specified current of 6 mA (normally sufficient for equalizing the current of four thrusters firing at 150 µN). Two power supplies were essentially needed to control the neutralizer: one for activating the thermionic cathode and another one to raise the potential of the anode used to extract the electrons.

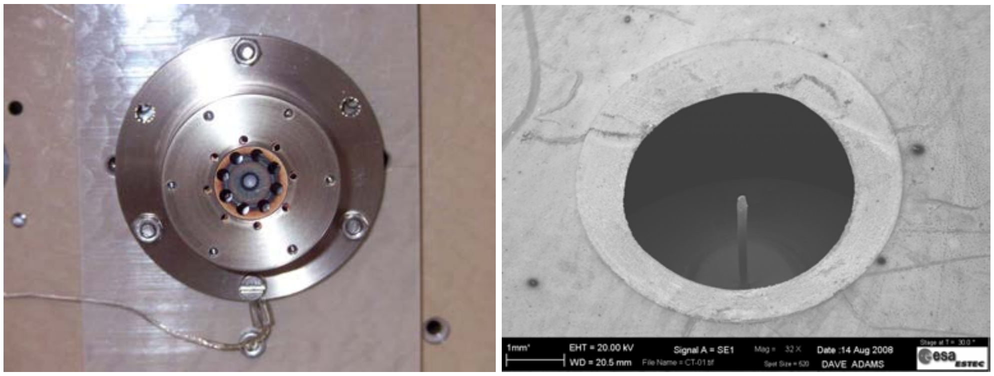

Figure 4. Test items (a) Microscope neutraliser and (b) SEM photography of ARC single emitter module

The electronic equipment was composed of carefully selected auxiliary equipment to insure the electrical insulation of the test items with respect to the laboratory ground. In particular, opto-couplers were procured to allow digital communication between the instruments and the data acquisition system (DAQ), and a high voltage isolation transformer was used to supply all the electronic equipment connected to the thruster and the neutralizer. Finally, a protection circuit composed of two Zener diodes with 1 μA leakage current and 200 V breakdown voltages was inserted between the floating potential and the laboratory ground to avoid excessive excursion of the floating potential which could have damaged the equipment and eventually created an unsafe situation for the test personnel. The impedance between the floating potential and the laboratory ground was then characterized by applying a biased voltage and measuring the leak current. An ammeter was installed to measure the current flowing between the casing of the neutralizer and the casing of the thruster to attempt verifying the equalization of currents in electrically floating configuration. The electrical scheme of the experimental setup is shown in Fig.5.

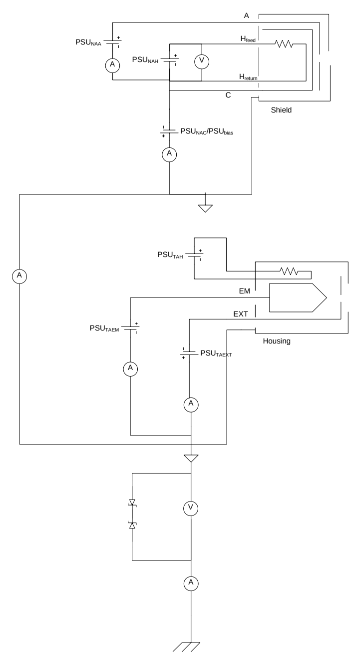

Figure 5. Electrical scheme of experimental setup

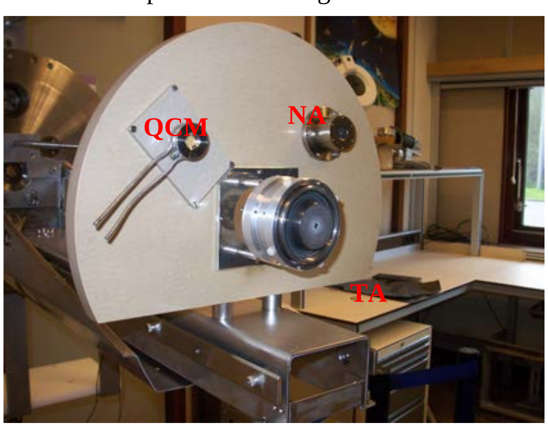

Figure 6. Mechanical interface

The thruster and the neutralizer were mechanically attached to a plate made of PEEK for obtaining satisfactory electrical insulation with the vacuum chamber's walls (see Fig.6). The test items supporting structure was itself bolted on a platform in the hatch which could be extended using a linear motion drive mechanism through the hatch into the main chamber. A quartz crystal micro-balance (QCM) was installed on the same PEEK plate to attempt measuring any deposition in an effort to assess the behavior of the neutralizer with respect to ground-testing contamination and, in particular, with respect to propellant contamination.

Thermocouples were placed at various positions in the vacuum chamber and on the thruster and the neutralizer, using Kapton tape to electrically insulate the test items from the DAQ. A Mass spectrometer was used to verify the levels of contaminants.

DAQ software was programmed under Labview™ to allow the control of the electronic equipment and the acquisition of measurements from the various instruments. Data was recorded 24/7 at a rate of 1 Hz.

III.Results

After the neutralizer was activated through a dedicated bake-out sequence of the thermionic cathode, a functional verification of the emission performances was carried out revealing some instability issues attributed to the “poor” vacuum level in the vacuum chamber (10^{-7} mbar). However, the neutralizer was able to generate more than 1mA which was more than sufficient for matching the thruster operational parameters. A characterization of the thruster performances was performed successfully and it confirmed the operational parameters specified by the manufacturer: the threshold for ion emission was obtained around 6 kV and the equivalent impedance between emitter and accelerator was 3.7 MΩ during firing operation.

When the thruster was off, the electrons extracted from the cathode of the neutralizer were all collected by the anode. The collection only by the anode indicates that space charge barrier was formed at a short distance behind the anode. As expected, there was not net electron current leaving the neutralizer without external influence.

The functional verifications of the thruster and the neutralizer were first performed with the floating potential in short with the laboratory ground. Later, the test items were operated independently in floating configuration in order to verify the electrical insulation of the setup. Regarding the neutralizer, there wasn’t any difference as there was no net electrons emission. However, sole operation of the thruster caused the floating potential to drift to negative values. On one hand, in a perfectly electrically insulated setup, this drift of the floating potential would have caused the Zener diodes to breakdown instantaneously. On the other hand, despite all precautions taken, a leak path of impedance evaluated to 2.9 MΩ was observed which caused the floating potential to drift slowly to negative voltage as the thrust was increased (see Fig.7a). Part of the leak was correlated to the 10 MΩ input impedance of the voltmeter used for measuring the floating potential. However, the origin of the additional leak path was unknown. Assuming an equivalent circuit as shown in Fig.7b), the impedance of the unknown leak path was 4 MΩ.

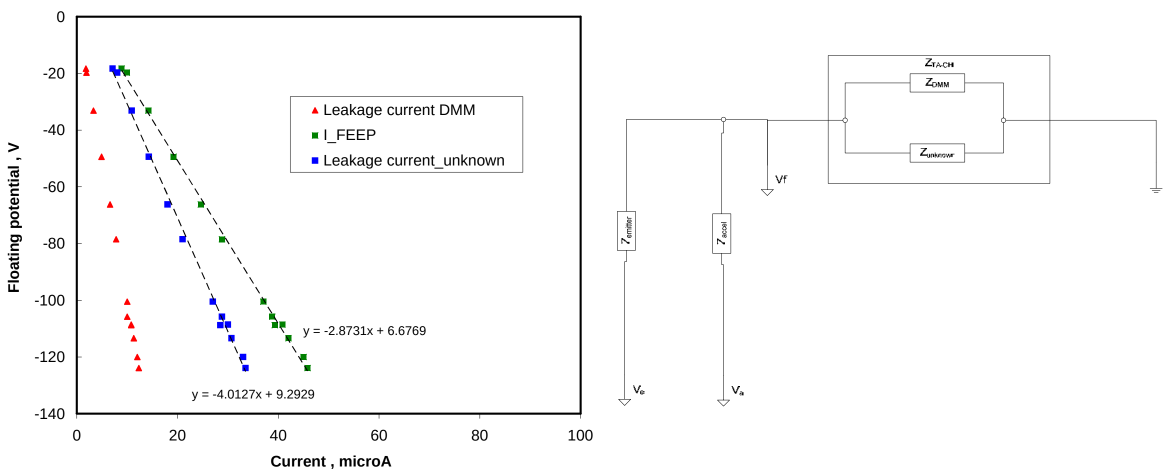

Figure 7. a) Floating potential vs. beam current during thruster operation; b) Equivalent circuit

The neutralization test sequence was representative of the FEEP system flight ignition: the neutralizer was first turned on, and then the thruster was ignited. Due to the leak path, the floating potential was first drifting toward negative voltage the same way it had been doing without the neutralizer turned on. However, once the floating potential reached approximately -35 V, the neutralizer began emitting electrons required to compensate the ions. The floating potential was still drifting toward more negative values as the thrust was increased, but it was still above -45 V at maximum thrust as shown in Fig. 8a).

It is interesting to note that the electronic current supplied by the neutralizer was exactly the complementary value of the leakage current (at a given value of floating potential) to equalize the beam current. Hence, the impedance between subsystem and laboratory was constant (no influence of test items’ operations) and the leak current was purely dependant on the floating potential. Assuming an equivalent circuit as shown in Fig.8b), the impedance between neutralizer and facility was 75 KΩ.

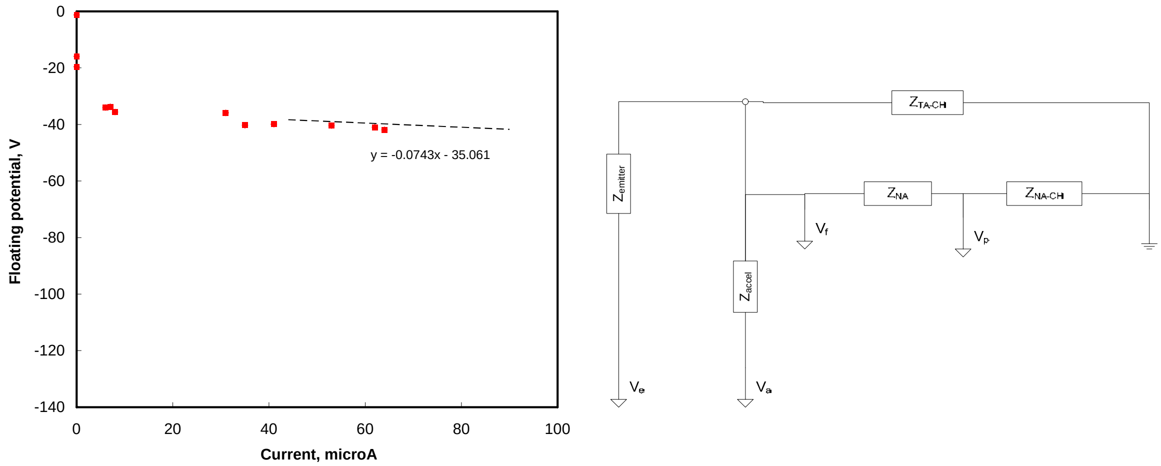

Figure 8. a) Floating potential vs. beam current during neutralisation test and b) equivalent circuit

The ammeter used to measure the neutralization current flowing between neutralizer and thruster only displayed low values below 1 µA. The QCM signal remained null while no Indium had been detected by the mass spectrometer. Nevertheless, it is believed that very low contamination of the neutralizer occurred due to the short time of firing. Moreover, the neutralizer was operated in pressure up to 10^{-6} mbar without more instabilities than at 10^{-7} mbar.

IV.Neutralizer simulations

Preliminary analyses demonstrated the feasibility of the neutralization concept through electro-static 2D-simulations of the electron beam trajectory from the neutralizer electronic optics toward a plasma modeled as a plane electrode located at a distance equivalent to the plasma sheath length (see Fig.9). Later, similar analyses were performed to verify the suitability of the neutralizer design with the LISA-Pathfinder which environment differed considerably from the Microscope ones: MICROSCOPE spacecraft will travel in a 700km Sun synchronous polar orbit. At such distance from the Earth, the plasma surrounding the spacecraft will be issued from the natural plasma of the ionosphere and the plasma density is between 10^4 and 10^6 cm^{-3}. Assuming an electron temperature of 1eV, the Debye length is between 7 mm and 4 cm. Simulations highlight that a plasma potential not larger than 100÷150 V is estimated to allow the dispersion of 5÷7 mA from the NA in the simulated ambient plasma; with dense plasma a drop of few tens of Volts may be expected. Fig.10 shows the relation between electrical field in front of the neutralizer and extracted current.

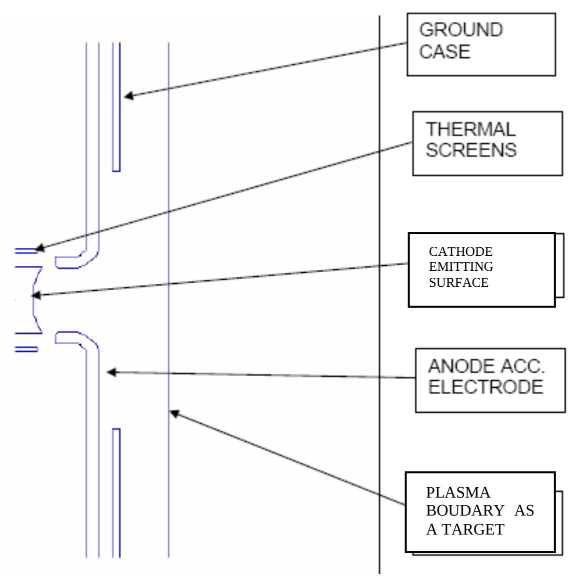

Figure 9. Neutralizer model for simulations (TAS-I)

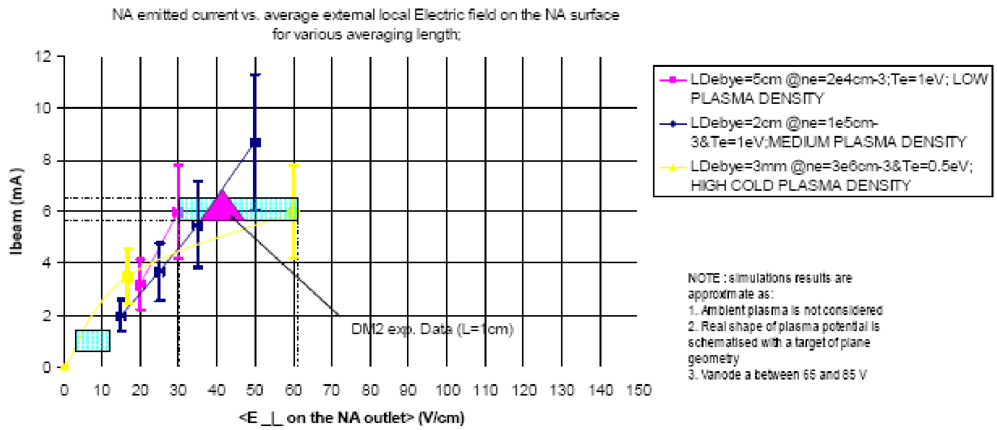

Figure 10. Neutraliser extracted beam vs. external electric field (TAS-I)

LISA-Pathfinder spacecraft will orbit at the Lagrange point L1. Most of the plasma surrounding the spacecraft will be induced by thruster operations, i.e. the ions from the beams and the charge-exchange collisions. Considering the location of the neutralizer with respect to the thruster, the CEX density is estimated to only 400 cm^{-3} (50cm Debye length assuming 2 eV electron temperature). Therefore, if the extraction of electrons was only driven by the presence of plasma, a spacecraft charging potential of some kVs might be estimated at the maximum requested current emission. However, the extraction of electrons is driven by the electric field in front of the neutralizer hence the presence of plasma is not strictly necessary. FEM simulations using the ©ANSYS code indicated that the electric field generated by the positive charges of the beam will significantly aid in pushing the electrons from the neutralizer outlet (see Fig.11).

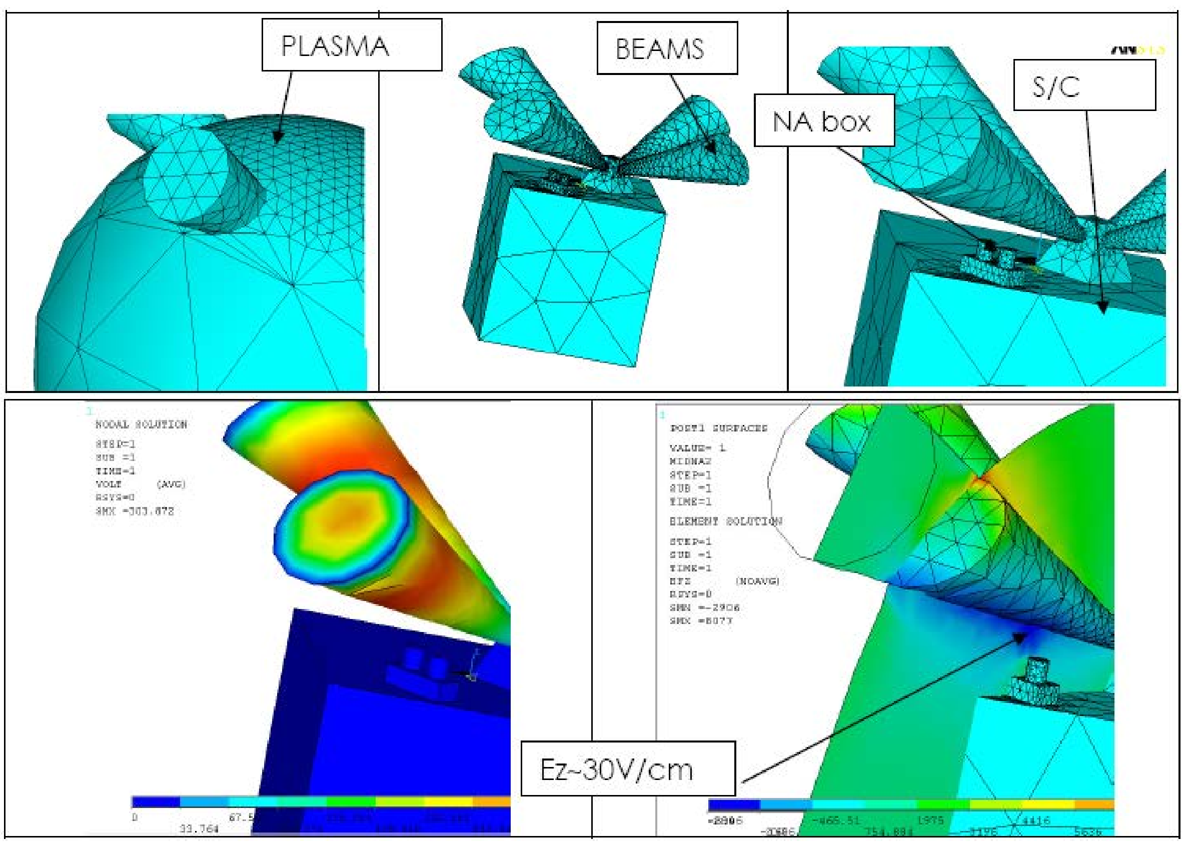

Figure 11. a) ANSYS electrostatic model and b) simulations results with 5mA beam

But analysis also revealed an issue if the thruster next to the neutralizer was not firing. Eventually, an alternative electrical scheme was selected for the neutralizer for giving the additional push to the electrons by biasing the cathode negatively. With such additional energy, simulations showed that a bias of -100 V was necessary to allow an emission and dispersion of ~6 mA in the plasma. On the other hand, if less electronic current was needed (not all thrusters firing), the spacecraft potential would charge positively (up to a maximum of +100V) until electrons have not enough energy to penetrate inside the environmental plasma and they would eventually be reflected back to the spacecraft.

V.Discussion

A. Secondary electron emission from facility walls

Ions impinging the walls of the test facility are causing various particles-matter interaction processes including secondary electron emission (SEE). It was questioned whether the secondary electrons could disturb the neutralization process. Practically, SEE was suspected to be the origin of the unknown leak path observed when the thruster was operated alone in floating configuration. The current produced by SEE is:

$$I_{SEE} = \delta \cdot I_{beam} \tag{1}$$

On one hand, for balancing the ion current, the electrons should leave the subsystem not the inverse. Indeed, assuming the secondary electrons would have traveled back to the thruster and deflected toward the casing because of the negative accelerator voltage, the net current leaving the subsystem would have been a fraction higher than the beam current. However, in grounded configuration (K closed) – not different from the floating configuration assuming secondary electrons would be attracted by positive potential of the beam – the leak current was equal to the beam current. On the other hand, the observation made during the neutralization test according to which the leak path was purely ohmic definitely discards any possibility that secondary electrons disturb the neutralization process at subsystem level. Nevertheless, it is not excluded that the secondary electrons locally balance the net charge density of the ion beam.

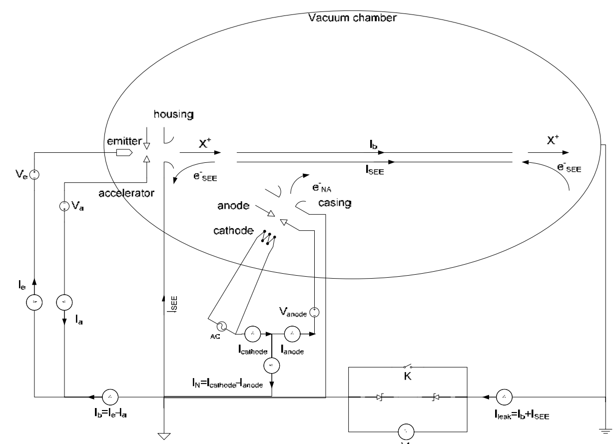

Figure 12. Hypothetical electrical scheme with SEE electrons travelling back to thruster

B. Plasma inside Gigant

The charged particles inside the test facility are the high-energy Indium ions extracted from the thruster, the low-energy Indium ions issued from charge-exchange collisions (CEX), the electrons extracted from the neutralizer and the secondary electrons emitted at the target. Secondary ion emission, photoemission and ionization of residual gas by the electrons are neglected.

At proximity of the neutralizer as it was located during the experiment, the low-energy Indium ions from charge-exchange collisions were most probably the highest density specie. As discussed previously, the neutralizer requires an external potential for the electrons to be extracted. According to the simulations, an electric field of ~1 V/cm is necessary to extract 100 µA from the neutralizer (see Fig.10). Assuming the plasma potential was most probably close to the laboratory ground, it means that the plasma sheath was λ_s=35 cm. Then using Eq.2, such a value correspond to an electron density of 10^4 cm^{-3} (choosing arbitrarily T_e=1eV and $\lambda_s=5*\lambda_D$). If the plasma is considered quasi-neutral, then the density of Indium ions next to the neutralizer can be estimated to 10^4 cm^{-3} as well.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 \cdot k \cdot T_e}{N_e \cdot q^2}} \tag{2}$$

C. Extrapolation of floating potential results

The CEX ions production rate density is proportional to the fast ions and neutrals densities as described in Eq.3.

$$\dot{N}_{CEX} = n_{In} \cdot n_{In^+} \cdot \sigma_{CEX} \tag{3}$$

If we assume that 1) both the density of neutrals and the neutrals-ions collision cross-section are constants and 2) the CEX ions density is proportional to the CEX ions production rate, then the density of CEX ions increases proportionally to the ion beam current (Eq.4).

$$N_{CEX} \propto \dot{N}_{CEX} \propto I_b \tag{4}$$

Furthermore, if we assume quasi-neutrality of the plasma surrounding the neutralizer, the Debye length decreases as described in Eq.5.

$$\Delta\lambda_D \propto \frac{1}{\sqrt{\Delta I_b}} \tag{5}$$

Therefore, by increasing the ion current from 100 µA to 6 mA, the Debye length decreases of roughly an order of magnitude, hence the electric field is increased by an order of magnitude at a fixed floating potential. According to the simulations (see Fig.10), an increase of the electrical field from 1 V/cm to 10 V/cm would allow extracting 3 mA at best. On the contrary, an electric field from 25 to 60 V/cm would be necessary for extracting 6 mA of electronic current. Hence an absolute increase of the floating potential of a factor between 2.5 and 10 with respect to the value achieved at 100 µA should be expected. For comparison, the test results were interpolated using linear and logarithmic models: at 6mA ion current, the linear interpolation predicts drift of the floating potential toward -480 V (factor 13.5) while the logarithmic interpolation predicts -60 V (factor 1.7).

D. Comparison with slit FEEP neutralization test

A similar test was performed at EPL on the Slit FEEP technology in April 2009 during which engineering models of the thruster and the neutralizer and the elegant breadboard model of the power control unit (PCU) from the LISA-Pathfinder project were tested. Unlike the experiments of 2007, the PCU was used to control the thruster and the neutralizer instead of the commercial power supplies, and a set of batteries were used to float the electrical setup instead of a high-voltage transformer. No leak path was detected and the insulation between subsystem and laboratory ground was better than 2 GΩ. Measurements have revealed a very similar behavior of the floating potential with respect to thrust level, but the absolute values were lower (see Fig. 13). For instance, the Slit FEEP floating potential was -16 V at 60 µA ion current whereas, it was measured at -40 V at same level of beam current during the experimental investigations in 2007.

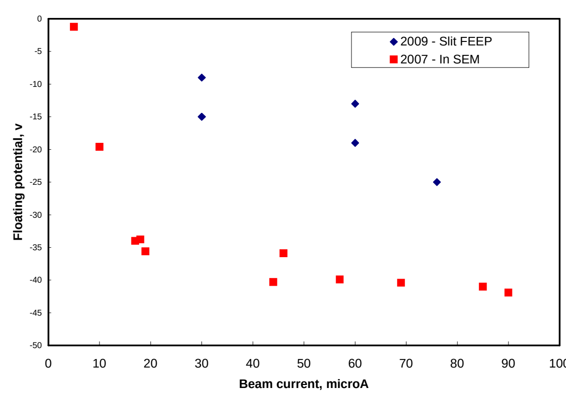

Figure 13. Floating potential vs. beam current during neutralization test

The discrepancy in absolute value can be attributed to variations in testing conditions such as the relative location of the neutralizer with respect to the thruster (see Fig. 14). Considering that the neutralizer was further away from the thruster in the latest testing activity (approximately five times further), it implies that the electric field generated by the ion beam in front of the neutralizer was in principle lower (the self-induced electric field being constant at a given ion beam current). Therefore, one would have expected the absolute floating potential to drift at higher values than the one achieved during the first experiments to be able to extract as much current. However, the inverse trend is observed. Hence, it suggests that the CEX ions density was driving the extraction of the electrons

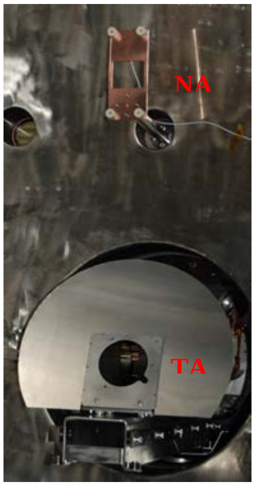

Figure 14. Test setup of slit FEEP neutralisation test

and that the density of CEX ions generated by the Slit FEEP thruster was higher than the one generated by the Indium ion source: rough calculation suggests that CEX ions density was 6 times higher in front of the neutralizer; if we assume a plasma density reduction law of $1/r^2$, it suggests that CEX ions density was 150 times higher at the same location of the neutralizer during the first experiment. For a same ion beam current, it means that either the density of neutrals was higher or that the collision cross-section was higher. Such a conclusion is fitting with the known high vapor pressure characteristic of Cesium which would cause a higher density of neutrals than Indium. In fact, the saturated vapor pressure of Cesium at its melting point (302K) is 0.3 Pa while the saturated vapor pressure of Indium at its melting point (430K) is $1.4x10^{-3}$ Pa. Hence, the ratio of the densities of Indium and Cesium modeled as perfect gases at pressures equal to their saturated vapor pressure and at their melting temperature is 311. Incidentally, such a value is the same order of magnitude of the ratio of CEX ions densities extrapolated from experimental results.

VI.Conclusions

The experimental investigations performed on a FEEP subsystem confirmed the neutralization process physical principle chosen for the Microscope and LISA-Pathfinder missions. Furthermore, simulated neutralizer performances and simple plasma model allowed correlating the trends observed experimentally with model predictions. Finally, comparison of results with a similar test campaign allowed highlighting intrinsic characteristics of two FEEP technologies using different propellant.

The thruster-facility interactions effects have been mostly neglected except for SEE which revealed to be not a source of disturbance for the neutralization process. However, the influence of pressure and the boundary conditions created by the walls of the vacuum chamber might have a higher impact on the neutralization process which make the absolute values of floating potential as measured in ground-testing not directly applicable in-flight on the spacecraft potential. Such considerations are applicable to the neutralization process as well as to electric propulsion performances. Use of experimental data to validate a model of the ground test is a first step toward more accurate and reliable simulations of flight model.

Acknowledgments

The authors would like to thank the various people of EPL who have contributed to a long and challenging testing activity which lasted between 2006 and 2007.

References

[1] Nicolini, D., “LISA Pathfinder Field Emission Thruster System Development Program”, *30th International Electric Propulsion Conference*, 2007

[2] E. Chesta, Y. André, L. Perraud, B. Pouilloux, P. Prieur, T. Tirolien J.-F. Roussel, T. Tondu, J.-C. Mateo Velez, “MICROSCOPE mission phase B propulsion system activities at spacecraft level: requirements consolidation and assessment of neutralization and contamination effects”, *30th International Electric Propulsion Conference*, 2007

[3] M. Capacci, G. Matticari, M. Materassi, “Neutraliser for FEEPs: review on the development status”, *31st International Electric Propulsion Conference*, 2009

[4] J. Gonzalez del Amo,G. Saccoccia, P.-E. Frigot, “ESA propulsion lab at ESTEC”, *31st International Electric Propulsion Conference*, 2009