STUDY OF THE SPT-20M7 LOW POWER UKRAINIAN HALL EFFECT THRUSTER*

A.V. LOYAN[1], N.N. KOSHELEV[1], T.A. MAKSYMENKO[1], A. LEUFROY[2], S. PELLERIN[2], T. GIBERT[2], N. PELLERIN[3,4], E. VERON[3,4], D. PAGNON[5], L. BALIKA[2], M. DUDECK[6]

[1] National Aerospace University "KhAI", 61070 Kharkov, Ukraine
E-mail: a.loyan@khai.edu
[2] GREMI, University of Orléans-CNRS, BP 4043, 18028 Bourges cedex, France
[3] CEMHTI, CRNS, 1D Avenue de la Recherche Scientifique, 45071 Orléans, France
[4] Université d'Orléans, 1 rue de Chartres, BP 6759, 45067 Orléans cedex 2, France
[5] LPGP, Université of Paris XI, 91405 Orsay Cedex, France
[6] Institut Jean Le Rond d'Alembert, University of Paris, 75005 Paris, France

Received January 24, 2011

In first, we present the performances of the lower power Hall effect thruster SPT-20M7 manufactured by KhAI (Ukraine). In second, we show that the ion energy distribution function in the plasma plume, and recorded by two Retarded Potential Analyser (KhAI and GREMI), exhibits two populations. In third, we indicate the chemical and microstructural changes of the insulated ceramics of the thruster.

Key words: Propulsion engine, plasma source, satellite.

1. INTRODUCTION

Hall effect thrusters (HET) for satellites set in geostationary Earth orbit and spacecrafts for planetary explorations are now well recognized as one of the most attractive device because of its high performances in specific impulse, level of thrust, low-propellant consumption, time of life (qualification tests are up to 10,000 hours as for PPS1350 for Snecma - France), possibility of several thousand successive ignitions with an absence of degradation of the intensity of the thrust, low divergence of the plume and storage capability of Xenon. This propellant is chosen because of its low first ionization potential level, lack of toxicity and mass).

For many years, Ukraine and France have initiated a common research program for the analysis of the physical phenomena appearing in the small Hall effect thrusters (from SPT20-M series) developed by KhAI (Kharkov-Ukraine).

* Paper presented at the 15th International Conference on Plasma Physics and Applications, 1–4 July 2010, Iasi, Romania.

Rom. Journ. Phys., Vol. 56, Supplement, P. 95–102, Bucharest, 2011

The performances of the models of this series from SPT20-M1 to SPT-20M7 (current model) have been increased (see figure 1) by successive optimizations of the magnetic topology, shape of the chamber and material. Theses HET thrusters are developed by KhAI for future operations onboard mini-satellites.

Previous measurements in the plasma plume have been carried out by optical emission spectroscopy in the KhAI and GREMI (Univ. of Orléans – France) vacuum facilities, by electrostatic probes in KhAI and by a thrust balance KhAI.

Recent measurements have been performed in KhAI and in GREMI with two retarded potential analysers (RPA). The first results on the ion energy distribution in the plume have been presented in [1] and an analysis of the origin of the different ion populations has been discussed in [2]. Complements on these results are presented in this paper.

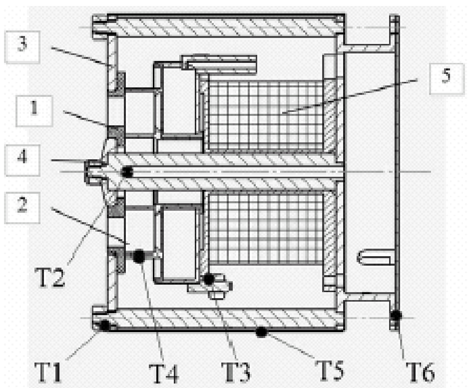


Fig. 1 – SPT-20M7 schematic view.

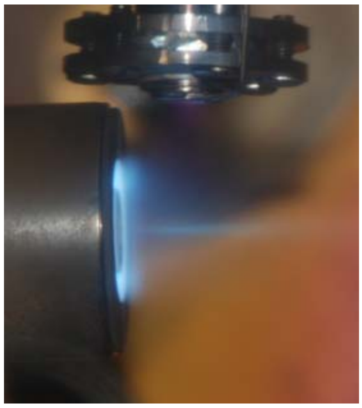


Fig. 2 – SPT20M6 plasma plume in the KhAI vacuum chamber.

2. THE SPT-20M HALL EFFECT THRUSTER

The SPT-20M7 Hall Effect Thruster from the Electric Propulsion Department of the National Aerospace University "KhAI" Kharkov in Ukraine was manufactured in mid 2007. The annular channel of the SPT-20 is constructed with two successive diameters and the size of the channel exit is 23 mm (outer ceramics) and 15 mm (inner ceramics). The magnetization coil (5) is set behind the first chamber containing the anode-gas distributor (figure 1). The maximum value of the radial magnetic field is obtained near the channel exit with a value of 20 mT (experimental data and modelling results) [5].

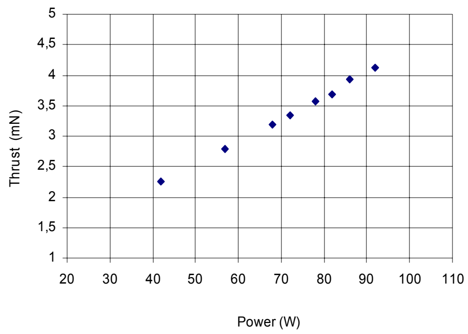


Fig. 3 – Thrust of the SPT-20M7.

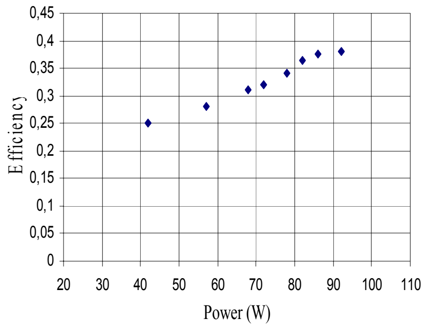


Fig. 4 – Efficiency of the SPT-20M7.

The SPT-20M7 thruster is a low power thruster running with an input electric power lower than 100 W, a Xenon mass flow rate of 0.1–0.35 mg/s injected in the chamber (the total mass flow rate is 0.48 mg/s) and a discharge voltage of 220–310 V between an anode and an external hollow cathode. The axial thrust is from 1 mN to 4.5 mN for an electric input power from 40 to 90 W (figure 3). The efficiency is in the range 25%–40% (figure 4) and the anode discharge current is in the range 0.15 – 0.4 A [1].

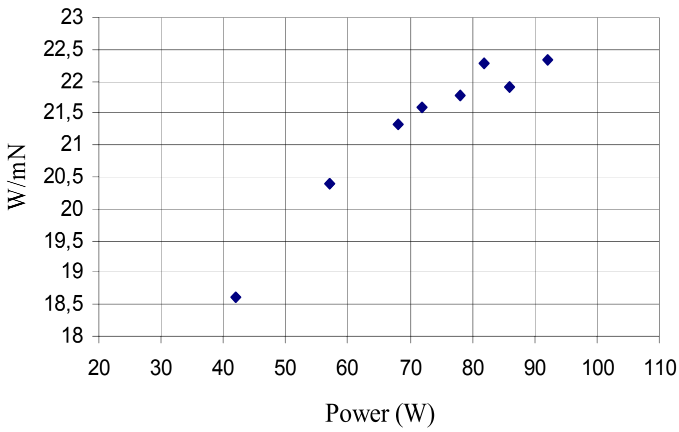


Fig. 5 – Power consumption per mN of the SPT-20M7.

3. ENERGY OF THE IONS

The ion energy distribution function (IEDF) of XeII was recorded and analysed in different points of the plasma plume by a Retarded Plasma Analyser (RPA) in the KhAI and in the GREMI facilities. The energy spectrum has been analysed in the GREMI facility (with a RPA manufactured by GREMI) for different angles, and for different discharge voltages from 200 V to 300 V. All the

IEDF exhibit two components: typically one is centered at around 200 V and the other below 150 V as shown on figure 6. The slow ions are present for different discharge voltages between 220 and 300 V and particularly for high angles (30°) related to the thruster axis. This effect has been observed both in KhAI and in the GREMI facility. Whatever the discharge voltage or the magnetic field are, the proportion of the low energy ions is always larger for wide angles than on-axis. For a discharge voltage of 300 V, on axis the total ion distribution is composed of 6% of slow ions and for 20°, the total ion distribution is composed of more than 50% of slow ions. The slower ions are thought to be produced either by conventional electron-neutral collision (neither than charge-exchange effect) in a lower potential place than the high energy ions one, near the exit of the annular channel and located close to the insulated walls (a detailled analysis of the origin of the low energy ions has been presented in [6]).

The presence of ions having an energy greater that the discharge potential has been experimentally observed in other facilities and predicted by a two-dimensional (2D) hybrid model [7]. The energy ion distribution at "KhAI" was obtained for a xenon mass flow rate of 0.216 mg/s, a discharge voltage of 300 V giving a discharge current of 0.245 A. The analysis of the recorded data with the measured electric potential distribution in the plume allows an estimation of the ionisation length (about 2 mm and beginning approximately a distance of 2 mm from the anode). The ion energy is constant as a function of the angle related to the thruster axis. However, the shape of the spectrum is strongly disturbed as the RPA is moving toward the periphery of the plasma plume keeping a main pic location. The results show that 95% of the ionic current is located in a half angle of 42 .. 46^{o} and only 30-35% of the ionic current is found inside an angle less than 20^{o}.

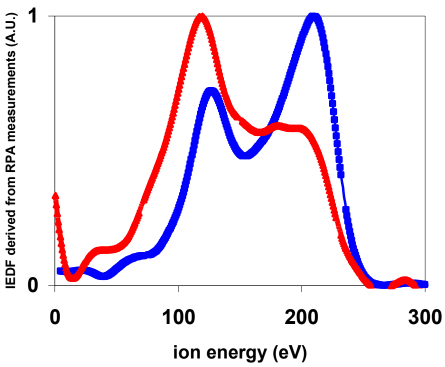


Fig. 6 – FDEI of XeII in the plume at 30 cm from the thruster exit plane for two different angles (-■- 0° on axis; -▲-15°) – GREMI. Operating conditions: U_d = 200 V, I_d = 145 mA, I_{coil} = 2.08 A, Xe anode flow 0.27 mg/s, Pressure 1.5 10^{-5} mbar.

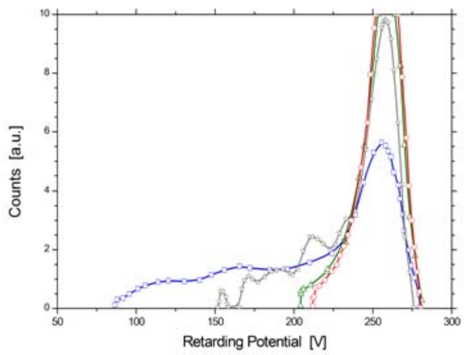


Fig. 7 – FDEI of XeII in the plume for different angles: 0° (○), 3° (Δ), 12° (☆) and 30° (□) - KhAI.

On figure 7 the measures recorded by the RPA probe for various angles in the plasma plume are presented. For angles more than 20^{o} a characteristic “tail” appears in the domain of small energies. The potential of the cathode was -20 V (to ground reference) and this difference is usually related to different thruster behaviors. We also observe a lack of ions with energy more than 280 V that correlates the previous remark.

4. ANALYSIS OF THE INSULATED SURFACES

The insulated surfaces have been analyzed by GSEM (Gaseous Scanning Electron Microscope) after one hundred hours of working. Chemical analysis has been carried on by EDX (Energy Dispersive X-ray) spectrometry. Ceramics are constituted with boron and nitrogen as major chemical elements (> 40 %at.), and oxygen and aluminium as minor chemical elements (< 6 %at.). The ceramics are then constituted essentially with Boron nitride (BN) phase. We suppose that AlN and/or AlON phases are also present (very few amount) and that oxygen participates to an oxide phase with boron (B_2O_3). Taking into account the ceramics geometry, it is not possible to confirm the hypothesis about chemical phases by usual technique as X-ray diffraction (excepted destroying the ceramics).

The ceramic microstructure outside the channel is showed in figure 8. This region is supposed not (or low) affected by Hall Effect motor working, in particular, ceramic ageing is not expected in absence of electrons and ions. So this region has been taken as reference for microstructure study of thruster ceramics. It is homogeneous and dense, with lighter crystals visible on the micrograph, enriched with aluminum.

A large microstructural change is observed in the channel, with regions exhibiting erosion or deposition phenomena. In the following, we will distinguish the channel top corresponding to the channel exit, and the channel bottom corresponding to the channel beginning, next to the anode and xenon distributor. On the cylindrical surfaces in the channel, a deposit is present (figures 9 and 10). At the top of the inner cylinder, microstructure study shows the presence of areas slightly enriched with metals: iron, silicon, nickel, copper (content: < 1 at.%) (figure 9, light area). In the channel, small grains are formed from columnar growth oriented perpendicularly to the cylinder axis. This microstructure is present at once on the inner and external cylinder but the grain size depends of the position in the channel (figure 10a and b). The surface ceramic is enriched with metals: iron, tungsten, nickel, copper (content: < 7 at.%) – chromium, silicon (content: < 3 at.%)), and oxidized. Boron is not detected in this deposit, and nitrogen rate is much reduced. Finally, xenon is also analysed on the channel wall (less than 1 at.%).

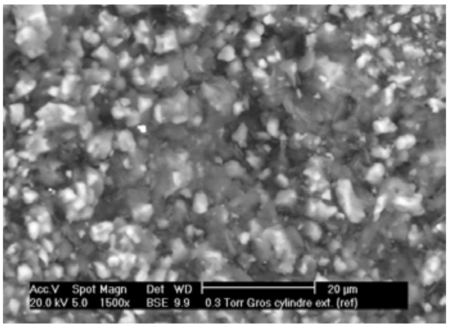


Fig. 8 – ‘Reference’: Microstructure of the isolated ceramics outside the channel.

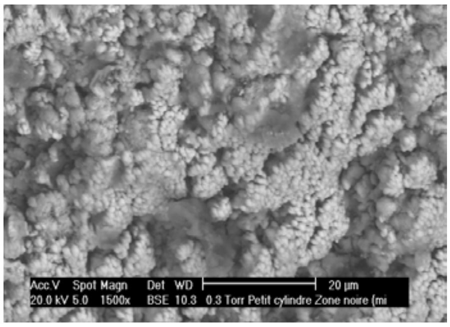
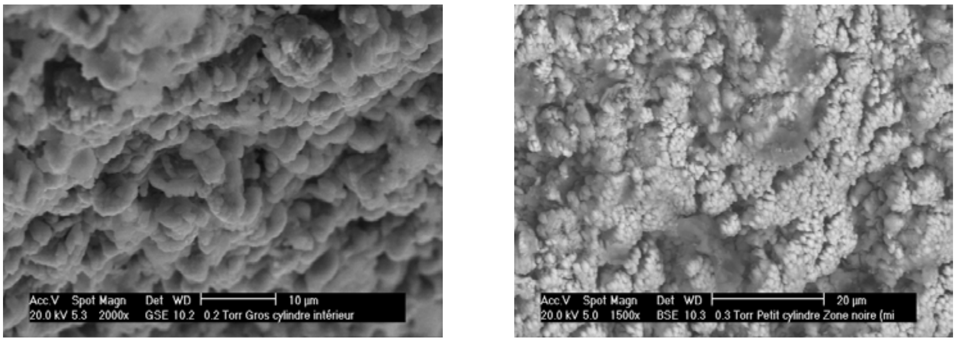


Fig. 9 – Deposit area on the inner ceramic at the top of the channel.



a) External ceramic b) Inner ceramic

Fig. 10 – Microstructure of the surface ceramics in the channel.

Erosion involves a strong modification of the external ceramic at the channel exit, forming a bevel on the surface perpendicular to the cylinder axis. This area is also covered with oxidized grains enriched with metals similarly to the channel surface, but also enriched with silicon (< 20 at.%). The origin of silicon is not very clear: it could come from the electrodes or the metallic structure of the thruster, or more probably from a pollution of the ground test facility related to the use of other thrusters equipped with ceramics in $BnSiO_2$.

The peripheral area of the bevel is slightly affected by erosion, with a strong decrease of boron and nitrogen content, but no metal deposit has been observed in this area (figure 11).

The ceramic surface corresponding to the channel bottom (next to the anode) is strongly altered (figure 12). Microstructure exhibits melting signs with large modifications of the microstructure and cracks formation. This area is enriched with boron but metal rates are rather low. The thruster running involves changes of the ceramics. Ion erosion phenomena induce geometric evolution of the external ceramic with bevel formation and consequently an increase of the plume divergence. Various metals (in particular iron) are present on the channel surface, due to electrodes and metallic pieces erosion or partial vaporization. The nitrogen and especially boron contents are strongly reduced in the channel, in agreement with optical emission spectroscopic measurements [2].

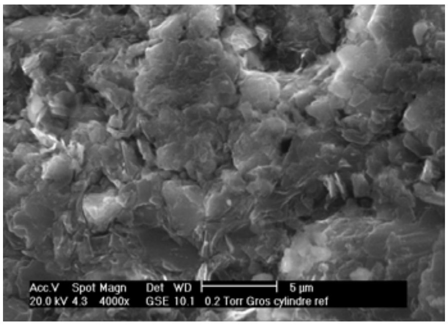


Fig. 11 – Microstructure of the top of the external ceramic, peripheral area according to the bevel.

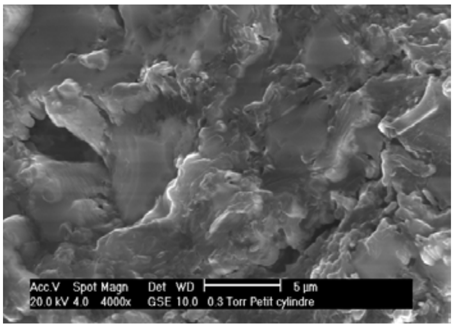


Fig. 12 – Microstructure of the inner ceramic next to the anode (bottom).

5. CONCLUSION

At the National Aerospace University “KhAI” was defined, manufactured tested and improved a set of successive SPT-20M HETs requiring an electric input power lower than 100W. The model SPT-20M7, equipped with BN ceramics, delivers a thrust from up to 4.5 mN with an global efficiency up to 40%. In parallel of campaigns carried out in the vacuum chamber of KhAI, other tests were performed in a vacuum chamber at the GREMI laboratory by R.P.A, and the erosion of ceramics was follow using GSEM and EDX spectrometry.

Acknowledgements. This research is supported by the French Research Group, GDR CNRS / CNES / SNECMA / Universités n°3161 "Propulsion par plasma dans l’espace”.

REFFERENCES

1. A.V.Loyan, T.A.Maksymenko, Performance investigation of SPT-20M low power Hall effect thruster, *30th Int. Electric Propulsion Conf.*, IEPC 2007, 16–20 September 2007, Firenze, Italy.
2. Pagnon, S.Pellerin, M.Dudeck, A.V.Loyan, T.A.Maksymenko, N.N.Koshelev, Ukrainian SPT-20 Hall Effect Thruster: Analysis of the Plume by Optical Emission Spectroscopy, *J. of Technical Physics,* **49** (2), 129–142 (2008).
3. V.Loyan, N.N.Koshelev, T.A.Maksylmenko, S.Pellerin, A.Leufroy, T.Gibert, D.Pagnon, M.Dudeck, Analysis of the plasma plume of the SPT-20M low power Ukrainian Hall Effect Thruster, *3rd European Electric Propulsion Conf.*, Versailles, 6–9 July 2009.

4. Bouchoule*,* T.Gibert, S.Mazouffre, Spectroscopic studies of XI and XeII emission in UHF discharge, *ICPIG*, Einhoven, North-Holland 2006.
5. Leufroy, Micropropulsion et diagnostics pour la propulsion spatiale, PHD thesis in French, University of Orleans, Feb. 15, 2010.
6. Leufroy, T.Gibert, A.Bouchoule, A.Loyan, N.Koshelev, T.Maksymenko, M.Dudeck, Laser Induced Fluorescence (LIF) and Retarded Potential Analyser (RPA) measurements of XeII in the plume of small Ukrainian Hall Effect Thruster SPT20-M, *6th Int. Spacecraft Propulsion Conf., Space Propulsion2010,* 3–6 May 2010, San Sebastian, Spain.
7. Bareilles, G.J.M.Hagelaar, L.Garrigues, C.Boniface, J-P.Boeuf, N.Gascon, Critical assesment of a two-dimensional hybrid Hall thruster model: Comparisons with experiments, *Physics of Plasmas,* Vol. 11, N°6, 3035–3046 (2004).