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ECRA thruster advances, 30W and 200W prototypes latest performances

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V. Désangles¹ and D. Packan, J. Jarrige, S. Peterschmitt
ONERA, DPHY, Université Paris-Saclay, F-91123 Palaiseau, France

P. Dietz, S. Scharmann, K. Holste, P. Klar
Institute of Experimental Physics I, Justus Liebig University, Heinrich-Buff-Ring 16, 35392 Giessen, Germany

The H2020 MINOTOR project focused on the study and the optimization of the ECRA thruster, an electric propulsion system for satellites. For the 30 W model of this Electron Cyclotron Resonance Thruster (ECRT) has been optimized. A 200W model has then been designed and optimized during tests campaigns. The performances of both prototypes were assessed at two different facilities: at ONERA in France and at Justus Liebig University in Germany. The significant improvement of performances of both thrusters is presented, with total thrust efficiencies as high as 50%, as well as erosion and lifetime assessment. The stability of the thruster for a constant point of operation was measured for one hundred hours of operation.

I. Nomenclature

ECRA	=	Electron Cyclotron Resonance Thruster developed at ONERA
T	=	Thrust
Isp	=	Specific Impulse
TTPR	=	Thrust to power ratio
B61	=	Vacuum chamber for EP devices at ONERA
JUMBO	=	Vacuum chamber for EP devices at Justus Liebig University
l	=	Inner conductor length
D	=	Inner conductor diameter
L	=	Outer conductor length

II. Introduction

ECRT is an electric propulsion concept that was first thought of during the 1960's both in the US [3-11] and in Japan [13-14], following the development of microwave (MW) engineering. Another group of studies were led in the US in the late 1980's [15-17]. All these original studies obtained low total thrust efficiencies and ended being stopped as competing technologies performed better. The high operating background pressure, around 10^{-4} mbar, and the few reliable direct thrust measurements available may explain that these studies miss the interest of the ECRT technology.

The research on ECRT started at ONERA, in France, in 2010 with the development of a 30 W ECRT named ECRA, a patent [18,19] and several PhD thesis focusing on the subject [1,2,20]. During these studies, low power permanent magnet prototype was designed, accurate thrust measurements were made [21,22], the higher efficiency of the coaxial coupling structure with respect to the waveguide one was demonstrated [23]. Using LIF and Langmuir probe measurements, the acceleration electric field was measured [24]. All these studies demonstrated

¹ Research Engineer, DPHY, ONERA, victor.desangles@onera.fr

the interest of the ECRT technology and motivated the MINOTOR project whose results are presented in the paper.

Recently, ECRT has gained global interest. Fundamental studies from University of Michigan are bringing answers on the role of electron to neutral collisions [25] and plasma fluctuations in the thruster plume [26]. Universities and companies are building their ECRT prototypes and characterizing their performances like the AVS Company and the Surrey Space Center [29, 30] and the University of Washington [27, 28]. These different prototypes are bringing knowledge about ECRT operation by testing new MW coupling, magnetic field topologies and alternative propellants like water.

The European Commission funded H2020 project MINOTOR aims at developing the ONERA thruster prototype Technology Readiness Level (TRL). All the different aspects of the thruster development are being tackled: prototype optimization and testing, numerical simulation tools development [31, 32], Power Processing Unit (PPU) development, system impact assessment and scaling up with the development of a 200 W thruster. The present paper recounts part of the results obtained during the prototype optimizations and testing studies. The third section introduces the experimental setups including the vacuum vessel and thrust balance used, the thruster prototypes description and their optimization. The Fourth section presents the observed facility effect. The fifth one summarizes the performances measured for the 30W prototype and the sixth one the performances of the 200 W developed thruster.

III. Experimental setups

A. Vacuum vessels: Jumbo and B61

The experiments reported in this paper have been conducted in two different vacuum vessels: the B61 at ONERA (French Aerospace Laboratory) in France which was used for the iterative optimization process of the ECRA thruster and the Jumbo vacuum vessel at Justus Liebig University (JLU) used for the two performance measurements campaigns.

The B61 vacuum chamber is 1 m diameter and 4 m long. Its pumping system is composed of a turbomolecular pump and a cryogenic panel for a total pumping speed of about 9,000 l/s for Xenon. It is equipped with a single hanging pendulum thrust balance with a 10 μ N resolution and a 10 mN maximum measurement range. This thrust balance is absolutely calibrated using a system of calibration weights.

The Jumbo vacuum chamber is 2.6 m in diameter and 5 m long. Its pumping system is composed of 5 turbomolecular pumps, a roots pump and cryogenic panels for a total pumping speed of 160,000 l/s for Xenon. It is equipped with a double inverted pendulum thrust balance. The balance is absolutely calibrated using a voice coil and calibration weights. The measurement range extends to 400 mN with a resolution of 10 μ N. This thrust balance has also been tested previous to this study using a gridded ion thruster RIT 4 from JLU with a very good agreement between measurement and expected thrust based on total current and acceleration voltage measurements.

B. ECRA Thruster description

The ECRA thruster is a magnetic nozzle electron cyclotron resonance thruster developed at ONERA. Microwave (MW) at 2.45 GHz are injected using a coaxial line that terminates in an opened coaxial cavity. The propellant is injected in this cavity and is ionized by the MW power. This cavity is limited radially by the outer conductor which is 27.5 mm diameter in the 30 W ECRA case and 70 mm in the 200 W ECRA case. To terminate the cavity a backplate transparent to MW is positioned at the back of the source. The magnetic nozzle is generated by an annular permanent magnet located at the back of the cavity. The permanent magnet is positioned such that the electron cyclotron resonance (ECR) at 2.45 GHz is located inside the cavity. During this study, only Xenon has been used as propellant gas but other gas such Krypton, Argon, Iodine, Oxygen, Air, Nitrogen, etc... could be used as no component of the thruster is sensitive to oxidation.



Fig. 1 (left) ECRA thruster geometry, (center) picture of a 30 W ECRA thruster, (right) operating ERCA thruster

Due to its simplicity of design, only two parameters define the operating point of an ECRA thruster. The mass flow rate of propulsive gas is measured using Bronkhorst EL-Flow series mass flow controller with either a 4 sccm or a 10 sccm Xenon flow range. These mass flow controllers have been calibrated using a home-made calibration platform built at JLU. The MW power is produced by a solid state laboratory power supply tunable in frequency and in power. It is measured using two couplers, two diodes and a circulator [2]. The MW power values given in this paper correspond to the power actually deposited in the thruster. By measuring the incident power and the reflected power at the vacuum vessel wall and by calibrating the loss in the MW line going from the wall to the thruster, one is capable to retrieve this deposited power.

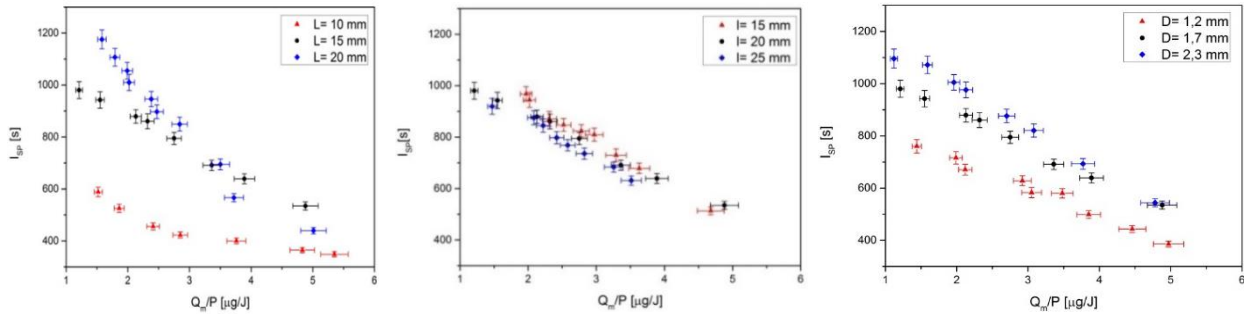


Fig. 2 Optimization of the different elements of ECRA using the evolution of its I_{sp} against the mass flow rate to power ratio, (left) the outer conductor length, (center) the inner conductor length and (right) the inner conductor diameter, from [1]

C. Optimization of the ECRA Thruster

During this study, the geometrical parameter of the plasma cavity have been optimized by a series of tests. In particular, the inner conductor of the coaxial structure length l , its diameter D and the outer conductor length L . The results of this optimization are shown on Fig. 2. It sets the dimensions of the thruster to 20 mm for l and L and to 2.3 mm for D . It is not shown on Fig. 2, but the diameter D can be increased higher than 2.3 mm without performances reduction [1], whereas an increase of L actually decreases the performances. We attribute this to the fact as the outer conductor gets longer, it cuts out some of the plasma trying to come out of the source and following the magnetic nozzle. Finally, increasing l over 20 mm does not change the performances but it does not seem preferable, as this part of the thruster will be more prone to vibrate or to be hit as it sticks out of the outer conductor.

Other optimizations such as the materials of the different components of the thruster, the divergence of the magnetic field, the MW frequency, the distance between the magnet and the backplate have undergone the same type of optimization processes. These results are out of the scope of this paper.

IV. Facility effects

A particularity of the ECR thruster is that its performances decreases as the background pressure inside the test vacuum chamber increases. This observation was first made during the first test campaign led at JLU in 2018. These measurements are presented on Fig. 3 (left). During this test campaign a non-optimized 30 W ECRA thruster was tested. Fig. 3 (left) demonstrates that while going from 10^{-5} mbar to 1.3×10^{-7} mbar of background Xenon pressure in the test vessel, the thrust produced by the thruster increases from 525 μN to 800 μN . It seems to plateau for pressure under 8×10^{-7} mbar. During the second test campaign, the same trend was observed on ECRA 200 W. The thrust increases from 2.15 mN at 4.5×10^{-6} mbar to 3.1 mN at 2×10^{-7} mbar. However, it is difficult to notice a plateau at low pressure. These measurements were performed injecting extra flow of Xenon using a second mass flow meter and an injection port located on the experimental vessel wall at the back of the thruster.

The thrust measurements made in Jumbo are compared to measurements made with the same thruster and with the same background pressure in the B61 on Fig. 3. The thrust measured in Jumbo is higher both for the 30 W and the 200 W thruster. The difference in measured thrust seems constant and equal to 150 μN in the case of the 30 W thruster. For the 200 W thruster, the only measurement point indicates a difference of about 300 μN . The source of this discrepancy is not known even though the size of the vacuum vessel is suspected. Further study exchanging thrust balance between facilities and artificially reducing chamber sizes may bring answers to this problem.

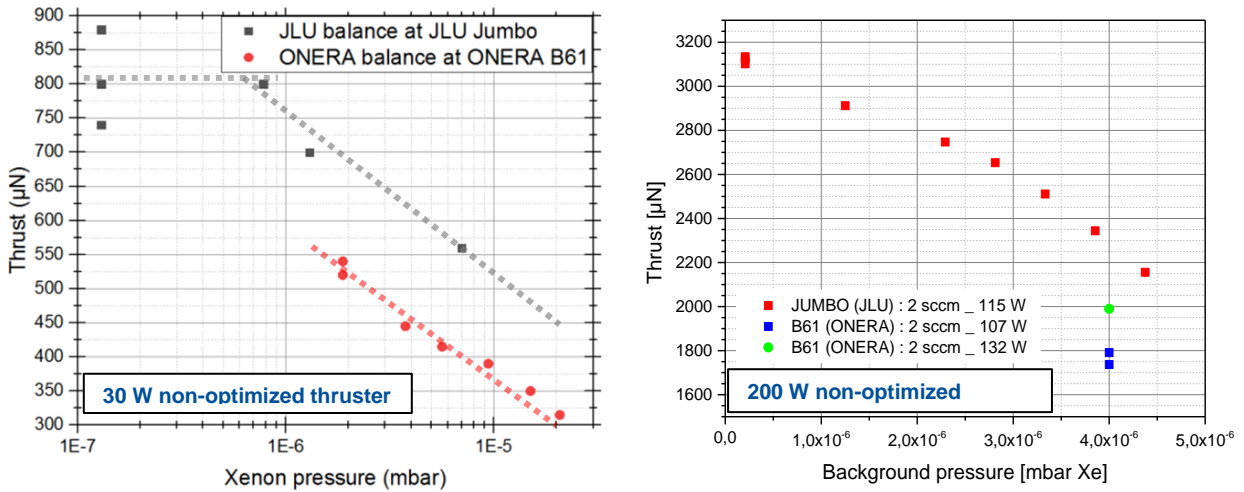


Fig. 3 Effect of the background pressure and facility effect on the thrust of (left) the 30 W thruster operated at 24 W and 1 sccm and (right) the 200 W thruster operated at 115 W and 2 sccm

V. 30 W Thruster performances

Two different 30W ECRA thrusters are compared in this section: a non-optimized thruster developed in 2018 and the final version of the thruster at the end of the project. Along this project, the total efficiency was the main indicator used to assess the positive impact of the modifications made and guide the optimization. While the initial thruster has an 8 % total efficiency measured in the B61, it already reached 13 % efficiency in Jumbo. For 1 sccm, the final version

of the thruster reaches about 40 % of total efficiency for a thrust ranging from 1.25 mN at 20 W to 2.0 mN at 50 W. The specific impulse is ranging from 1300 s at 20 W to 2200 s at 50 W.

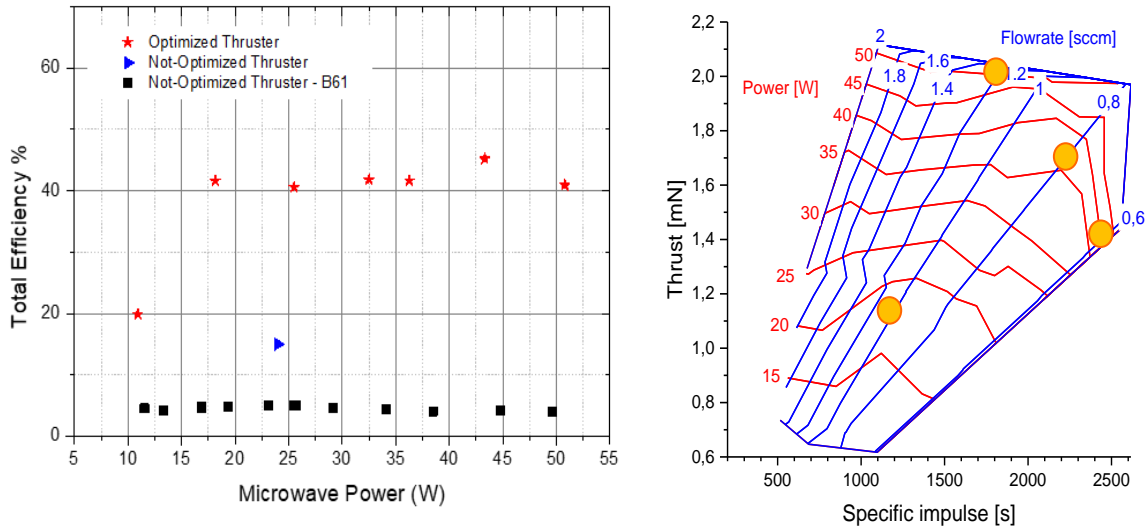


Fig. 4 Performance figures of: (left) two versions of the 30 W ECRA thruster tested in the B61 and in the Jumbo vacuum chamber, the total efficiency against the MW power is measured for a constant flow rate of 1 sccm and (right) thrust against specific impulse map of the final version of the 30 W ECRA thruster tested in Jumbo vacuum vessel for a chosen range of operating parameters (see text)

A complete performance map has been measured whose results are presented on Fig. 4 as the thrust against the specific impulse. The power has been varied from about 10 to 50 W and the mass flow rate from 0.6 to 2 sccm. Below 10 W and below 0.6 sccm, the thruster tends to switch off which sets the lower limit of this map. For high power, the thruster potential rises above 400 V and the thruster also switch off by itself. This limit depends on the mass flow rate explaining why the map stops at 45 W for 0.6 sccm and at 50 W for higher flows. However, this point is not reached for most of the mass flow rate presented here and the thruster could have been operated at higher power. The mass flow rate can also be increased above 2 sccm. The choice to limit the map to 2 sccm and 50 W is driven by the decrease in total efficiency of the thruster at high flow rate and high power.

Some set points of the thruster operation from Fig. 4 (right), represented by an orange dot on the map, are summarized in Table 1. Depending on the operating regime, the 30W ECRA optimized thruster can reach maximum thrust of 2.0 mN, a maximum Isp of 2500 s, a maximum TTPR of 65 mN/ kW and a maximum total efficiency of 50 %.

VI. 200 W Thruster performances

The main design of the 200 W thruster is a scale up of the 30 W ECRA thruster. Targeting 200 W, the diameter of the plasma source has been increased in order to conserve the power per backplate surface area from 30 W to 200 W. There are three different versions of the 200 W ECRA thruster that have been tested through this study. They are labeled v2, v3 and v4, v2 being the first version and v4 being the last version. Only the v4 version integrates all the optimizations defined by the 30 W ECRA optimization study. The version v2 has first been tested in the B61 vacuum vessel and demonstrated an 8 % total efficiency at 4×10^{-6} mbar (Xe) (Fig. 5 Performances figures of (left) three versions of the 200 W ECRA thruster tested both in the B61 and in the Jumbo vacuum chamber and (right) thrust against specific impulse map of the final version of the 200 W ECRA thruster tested in Jumbo vacuum vessel Fig. 5 (left)). The same thruster version shows a 20% efficiency when tested in Jumbo at 2×10^{-7} mbar (Xe) operating at 2 sccm over a range of power going from 60 to 150 W. The version v3 and v4 have better performances. It demonstrates

that the design improvement made on the 30 W thruster are improving also the 200 W design. The total efficiency exhibit a bell shape curve against the power at constant flow rate. This is typical both for both the 30 W and 200 W thrusters. The maximum efficiency reaches 50 % for 80 to 100 W.

Table 1 Chosen operation set point summary of the 30 W ECRA thruster tested in Jumbo vacuum chamber

Operation set point	Q_m [sccm]	Power [W]	Thrust [mN]	I_{sp} [s]	TTPR [mN/kW]	Thruster efficiency (%)
<i>Initial Performances</i>	1.0	24	0.8	840	33	13
<i>Final Performances</i>	1.0	25	1.5	1580	60	44
High thrust	1.2	50	2.0	1800	40	35
High Isp	0.6	45	1.4	2500	31	40
High TTPR	1.0	17.5	1.1	1200	65	40
High efficiency	0.8	35	1.6	2200	46	50

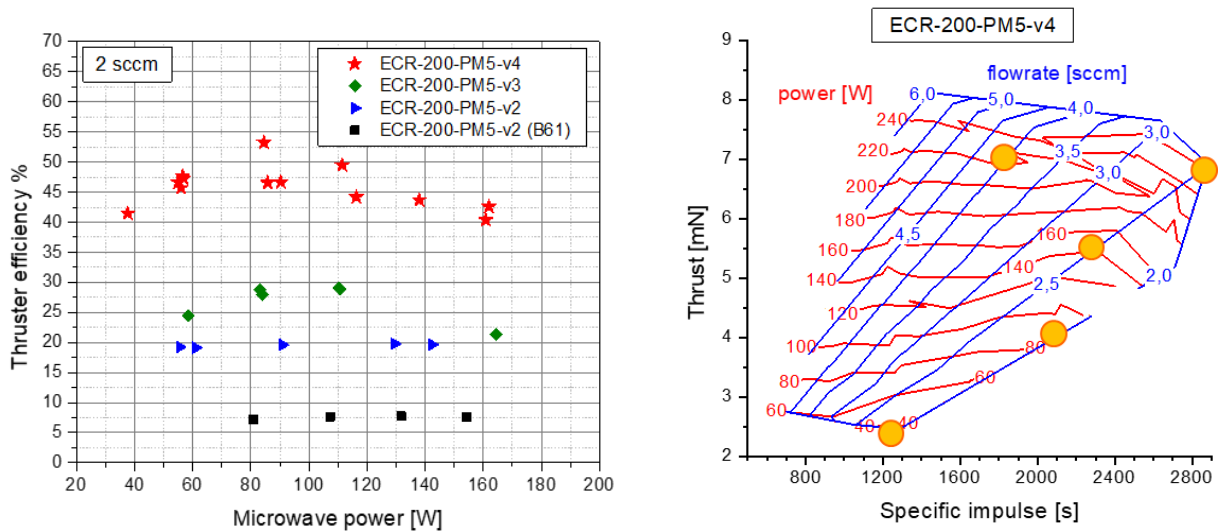


Fig. 5 Performances figures of (left) three versions of the 200 W ECRA thruster tested both in the B61 and in the Jumbo vacuum chamber and (right) thrust against specific impulse map of the final version of the 200 W ECRA thruster tested in Jumbo vacuum vessel

A complete performance map (Fig. 5 (right)) has been measured similarly to the 30 W thruster with the same consideration used to fix the limit of map parameters. Five chosen operating points represented as orange dot on Fig. 5 (right) are summarized in Table 2. Depending on the operating regime, the 200W ECRA v4 thruster can reach

maximum thrust of 7.15 mN, a maximum Isp of 2900 s, a maximum TTPR of 66 mN/ kW and a maximum total efficiency of 53 %.

Table 2 Chosen operation set point summary of the 200 W ECRA thruster tested in Jumbo vacuum chamber

Operation set point	Q_m [sccm]	Power [W]	Thrust [mN]	I_{sp} [s]	TTPR [mN/kW]	Thruster efficiency (%)
High thrust	4.1	221	7.15	1821	32.4	28.9
High Isp	2.5	245	6.93	2879	28.3	40.0
High TTPR	2	38	2.47	1289	65.6	41.5
High efficiency	2	85	4.19	2190	49.6	53.3
Intermediate	2.5	146	5.56	2310	38.1	43.2

VII. Erosion, lifetime and stability tests

A. Erosion and lifetime

The main erosion phenomenon occurring when the thruster is firing is located on the inner conductor. This conclusion was made both by looking at the thruster pieces after hundreds of hour of operation and by weighting the inner conductor. The erosion rate of the inner conductor for the 30 W ECRA thruster has been measured in the B61. The inner conductor has been unmounted and weighted every tens of hours for a total time of sixty hours of operation. The mass loss appears to be constant and equal to 0.11 % of the initial per hour. It implies that the inner conductor would lose 50 % of its mass in 500 hours.

The erosion of the 200W thruster have been measured only one time. During a 100 hours test in Jumbo the inner conductor has lost 3% of its total mass. Following the hypothesis that this mass loss is constant as in the 30 W ECRA thruster case, the loss rate would be of 0.03 % of the total mass per hour. It implies that half of the inner conductor would be eroded after 1,700 hours.

This erosion of the inner conductor is the only source of potential failure identified so far. It is possible that for test going up to thousands of hours other sources of failure may appear so these tests should be conducted in the future. Finally, it has been demonstrated on previous prototype that increasing the inner conductor diameter above 2.3 mm does not reduce the thruster performances. Those results needs to be verified on the latest prototypes. The increase of

the total mass of the inner conductor, going as the square of its diameter, may allow a large increase in inner conductor lifetime.

B. Stability test

The thruster ECRA 200 W in its v4 version has been fired in the jumbo vacuum vessel for 100 hours. The thruster have been fired continuously during 9 hour for four days first and then continuously for 64 hours. The operating point was set to 100 W and 2.5 sccm. As shown on Fig. 6, the thrust produced by the thruster is very steady and equal to 5 mN. The measured Isp is equal to 2500 s, the TTPR is 46.5 mN/kW and the total efficiency is 56 %. It demonstrates the thruster stability and reliability for several tens of hours of continuous operation.

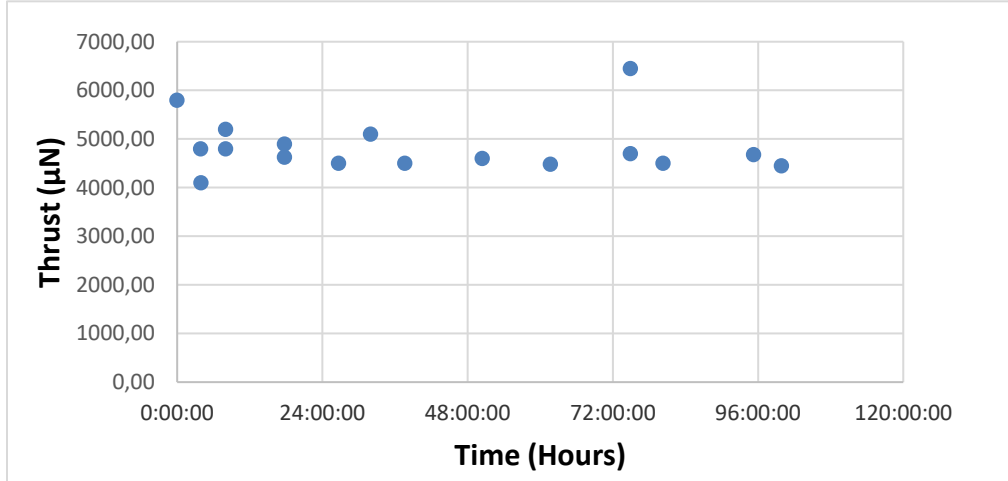


Fig. 6 Stability test performed on the thruster ECRA 200 W v4 in Jumbo

VIII. Conclusion

During the H2020 MINOTOR project the ECRA thruster developed at ONERA have been optimized in order to increase its performances. A second thruster working at 200 W has been developed from the first prototype operating at 30 W. The optimization of the thrusters allowed to improve considerably the thruster performances while measured in similar test conditions, and obtain total thrust efficiencies as high as 50 %. The effect of going from the B61 chamber to the Jumbo chamber is critical. It can be explained partially by the better background pressure but not completely. Experiments where the background pressure is artificially increased in Jumbo to meet the B61 conditions demonstrated that there is a chamber dependent effect. It is believed that the size of the vacuum chamber plays a role but it has not been demonstrated. Further work may focus on performing experiments in another high pumping rate facility and try to distinguish pumping speed to other facility effects. Lastly, the erosion and stability test demonstrates that the thruster lifetime of the 200 W thruster can be estimated to be over 1,000 hours. The thruster showed very stable operation during 100 hours.

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