HT-100 Hall thruster characterization tests results

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The paper deals with the preliminary results of several tests carried out at Alta during the last year on different low-power Hall thruster models, with nominal discharge power < 200 W. All configurations have been obtained by scaling from the HT-100 design, a 100-W Hall thruster with permanent magnets, under development at Alta since 2003. The new configurations include a new model with the same nominal power of HT-100, the HT-100b, but with a modified magnetic circuit for achieving higher lifetime and a model scaled up to a nominal power of 175 W, the HT-100c. The different models have been tested with the K&R cathode, an industrial electron source, used during HT-100 development, but also with new cathodes that, although not yet optimized for the power class of interest, are certainly more appropriate in terms of flow rate and power consumption. The test campaign is still on going; the results available until now seem to give interesting indications on magnetic field pattern and cathode coupling in low power Hall thrusters.

I. Introduction

Alta's HT-100 Hall thruster [1-5] is the smallest and lowest power HET ever developed in Europe. Its main design feature is the use of permanent magnets instead of electromagnets for the generation of the magnetic field. At its design point, HT-100 delivers a thrust of 4.5 mN and a specific impulse of nearly 1000 s with a discharge power of 100 W; the highest performances in terms of thrust (12 mN) and specific impulse (1600 s) were achieved at a discharge power level of about 275 W. HT100 has been conceived for application to microsatellites with limited power and volume budgets for the EP system [6-7]; nevertheless its performance is of interest also for coarse maneuvers in scientific missions and drag compensation in very-LEO Earth Observation applications [8].

During the development phase HT-100 has undergone several characterization and long-firing campaigns, for a cumulative firing time of nearly 600 hours on a single unit [3] and also including a test on a two-engine cluster [4].

More recently the thruster has reached its final configuration, named HT-100b [5], where the mechanical design has been improved and the magnetic circuit modified in order to increase the thruster lifetime.

At the same time, under ESA TRP program, the thruster has been scaled up to the nominal point of 175W, 8mN in order to satisfy performance requirements of a multi-mission scenario. The new thruster, named HT-100c [5] has the same external diameter of HT-100b but a larger chamber diameter; the magnetic circuit is still based on permanent magnets.

In the last year several tests have been carried out at Alta on both HT-100b and HT-100c in order to verify the design modifications with respect to HT-100. In particular HT-100b has fired during several test campaigns almost at fixed operating point for a cumulative time of 450 hours and the chamber erosion compared with that of HT-100

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at the same firing time. The same thruster, after changing ceramic chamber, has been then tested with a new cathode supplied by National Aerospace University KhAI (Kharkiv Aviation Institute). Concerning HT-100c, it has been tested with a cathode provided by Thales Alenia Space Italia (TASI) as subcontract of Alta in the frame of the ESA TRP project; the test aimed to the performance mapping of HT-100c.

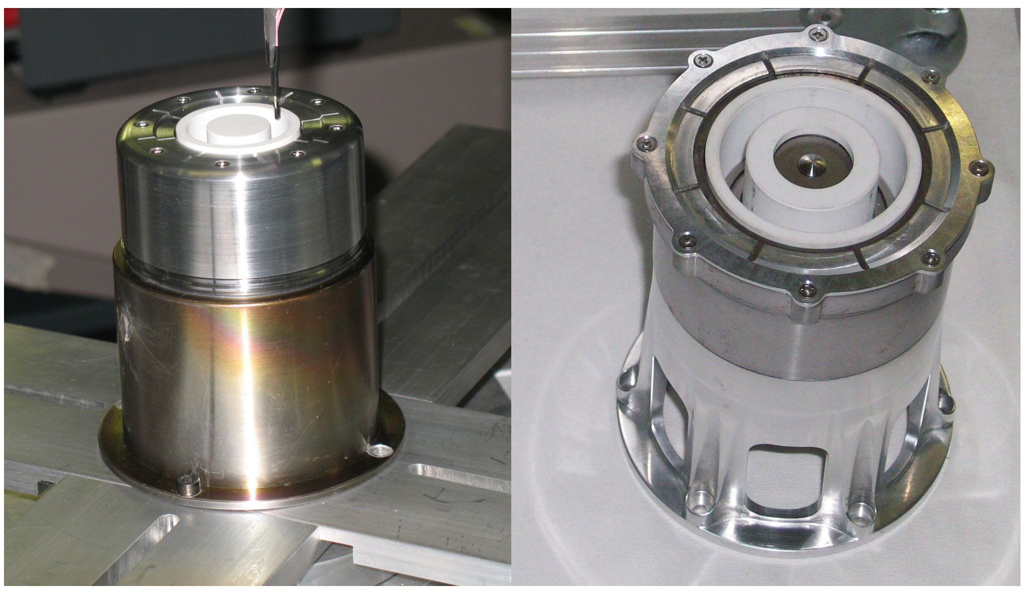
The present paper deals with these experimental activities on HT-100b and HT-100c carried out in the last year; in particular in section II the single test articles are described, while in section III the results of the different experimental campaigns are presented and discussed.

II. Test articles

The table below gives the main elements of the test campaigns carried out in the last months on HT-100b and HT-100c.

Table 1. Recent test campaigns on HT-100b and HT-100c

Test articles	Type of test	Period
HT-100b + K&R cathode	endurance	January 2010-March 2011 (at intervals)
HT-100b + KhAI cathode	short characterization	June 2011
HT-100c + TASI cathode	performance mapping	March-July 2010



a) b)

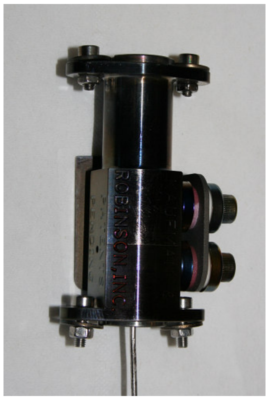
Figure 1. Both HT-100b (a) and HT-100c (b).

The K&R cathode is a heater-less cathode for use with industrial plasma sources. It has been used for the endurance of HT-100b in order to allow the comparison in terms of ceramic erosion with HT-100 that ever used this cathode both during characterization and long-firing tests.

The first of the three next pictures (Figure 2) shows the Kauffman & Robinson cathode and the related table describes the main characteristics of this electron emitter. It's easy to note how big is the value of mass flow rate of this cathode (0.2-3 mg/s in Xe) respect to typical value of this parameter for the anode (0.5-1 mg/s in Xe).

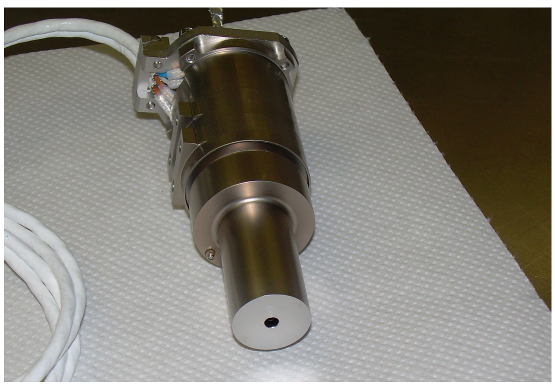
The TASI cathode is shown in Figure 3 that also reports in the related table its main technical specifications. The main characteristics of this cathode are the presence of the heater, the weight that is about half of the previous one and the considerably lower working mass flow rate (0.1-0.2 mg/s in Xe).

The KhAI cathode has been developed for space application. Its main features are the limited dimensions, also due to the absence of the heater and the low sensitivity of the emitter to contamination. The cathode and its main characteristics are presented in Figure 4.



Parameter	Value
Discharge Current, *A*	1÷2
Max Discharge Current, *A*	10
Ignition tension, *V*	600
Xe MFR, *mg/s*	0.2÷3
Mass, *g*	200

Figure 2. K&R cathode: picture and main technical specifications



Parameter	Value
Discharge Current, *A*	0.3÷1.2
Max Discharge Current, *A*	2
Xe MFR, *mg/s*	0.1÷0.2
Heating Power, *W*	<50
Lifetime, *h*	5000÷8000
Cycles	10000
Mass, *kg*	<0.1

Figure 3. TASI cathode: picture and main technical specifications

Parameter	Value	Notes
Working Current, *A*	0.5 – 1.5	Long duration conditions
Near SHC potential, V	24-16	Correspond with current
Xe MFR, *mg/s*	0.03-0.12	Complex dependence from current
Ignition tension, V	700	
Lifetime, *h*	20000	
Size, diameter-length, mm	10/46	Without gas tube and electrical cable, without locating flange
Mass, *g*	9.2	Without gas tube and electrical cable

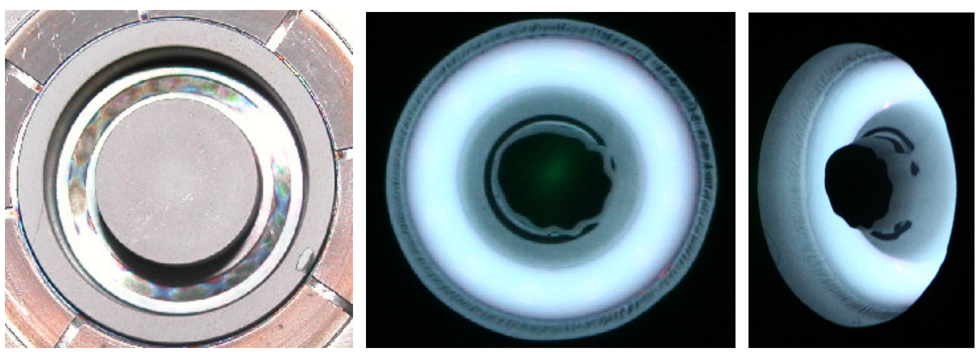
Figure 4. KhAI cathode: picture and main technical specifications

All test campaigns have been carried out in Alta IV4 vacuum facility; the thruster has been mounted on a thrust balance, the same used in the past for HT-100. To complete the characterization tests Faraday probes, which are part of IV4 facility diagnostic instruments, were used for beam current distribution analysis. An accurate description of the facility, thrust balance and beam diagnostics can be found in Ref. 3. Xenon with a purity grade of 4.8 or superior has been used as propellant. The Electric circuit is based on laboratory power supplies. Data acquisition and control system is completely automatic; it has been developed in Labview language.

III. Results and discussion

A. HT-100b + K&R cathode

The test on HT100 has given good results in terms of performances, as said before, but after a certain amount of hours the ceramic chamber erosion level achieved not negligible dimension. In Figure 6 the picture of the initial shape of the ceramic chamber (a) is compared to the shape after 450 hours of firing, from central view (b) and lateral view (c).



(a) (b) (c)

Figure 5. HT-100 erosion studies pictures: beginning of the test (a) and while firing after about 450 hours (frontal view (b) and lateral view (c))

So the principal goal in upgrading HT-100 model was to decrease the ceramic erosion rate in order to increase thruster lifetime. To obtain this scope, the original magnetic circuit, as said, has been modified. To verify this improvement a direct measure on the internal and external ceramic walls has been made after about 250 and 450 hours of firing time with K&R cathode. Then the results have been compared with the measure taken after 250 hours of firing time on the original model with K&R in 2007. In both cases the thrusters have worked at fixed operating parameters at a power of about 150W for most of the firing time. The profiles reconstructed have been graphically superimposed in Figure 6. Even after 450 hours of firing the erosion in the new thruster is lower than in the original HT-100 after 250 hours, for almost all measurement points (expressed in angular terms, where 0° indicates the cathode position).

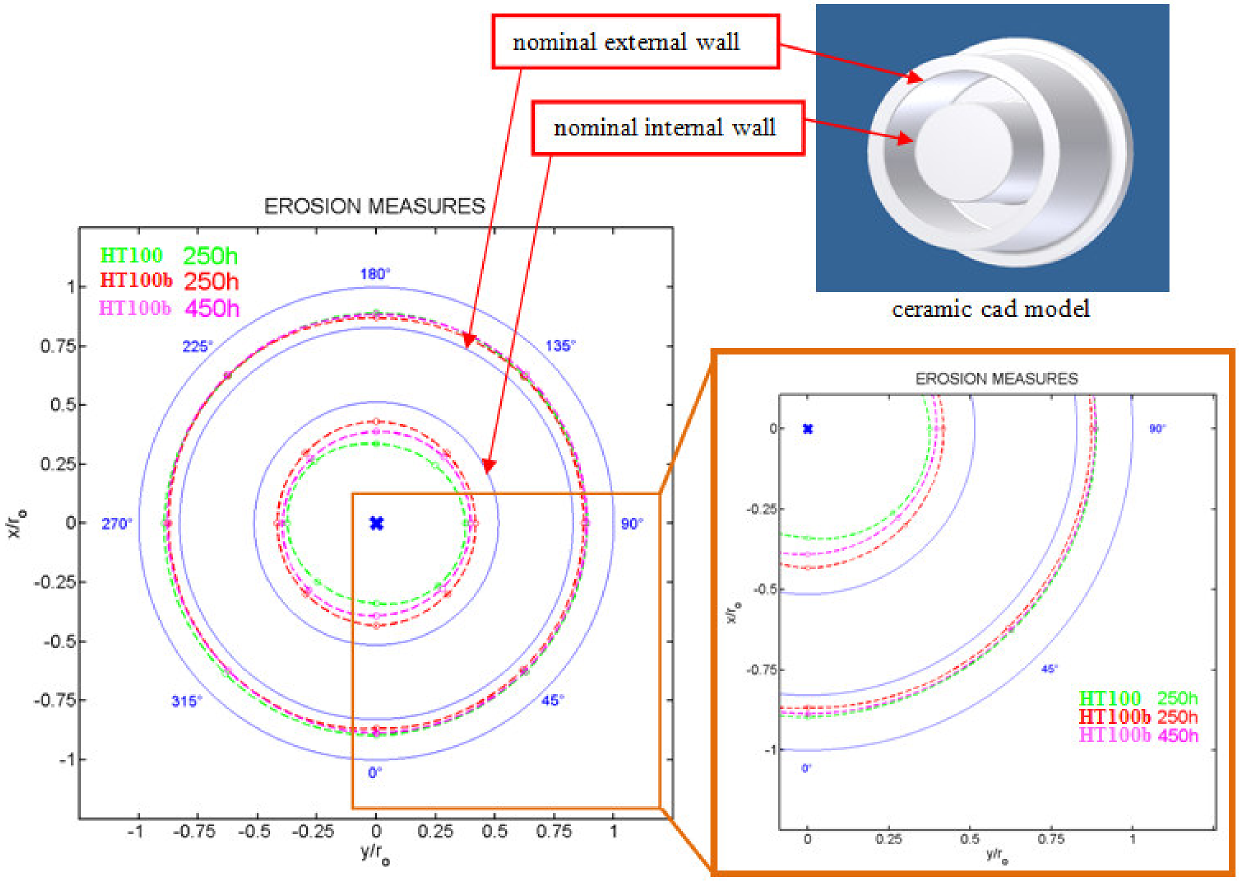


Figure 6. Comparison between the erosion of the internal and external ceramic for HT-100 and HT-100b after 250 hours of firing and for the HT-100b after 450 hours of firing..

The values have been so compared separately for each measurement point and the result is shown in Figure 7 and Figure 8. The erosion rate in the graphics has to be intended as the rate between the final and the initial thickness for the external ceramic and the rate between the final and the initial radius for the internal one. The results showed that in average the erosion rate for the external part (Figure 7) has decreased from 37% to 27% in the first 250 hours of life, so a 10% of the total thickness was gained; after 450 hours of firing time the erosion rate was in average about 33%, again under the level of erosion for the HT100 model after 250 hours.

For the internal part of the ceramic (Figure 8) the results have been even better: passing from 30% to 17% in average, so the 13% of the thickness was gained in the first part of the test, while in the second part, after 450 hours of total firing time, the rate achieved 23%, still 7% under the old model erosion rate after 250 hours of firing time.

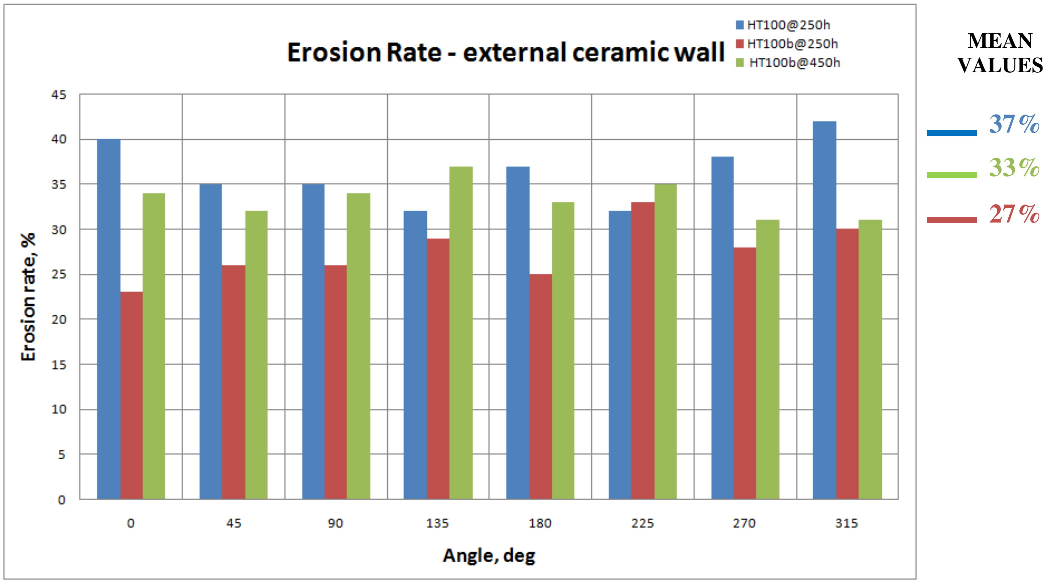


Figure 7. Erosion rate for external ceramic wall.

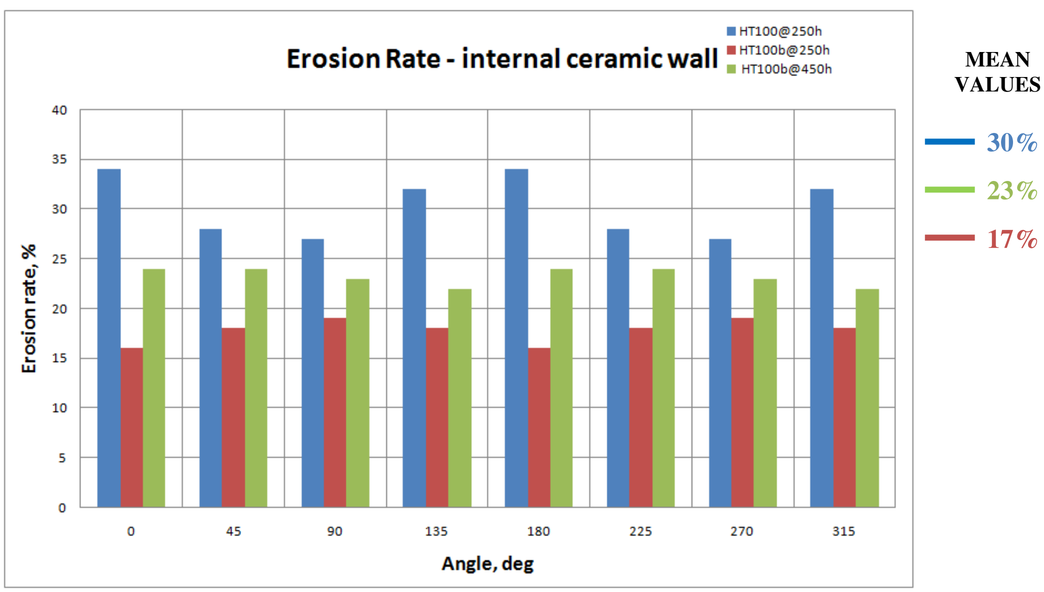
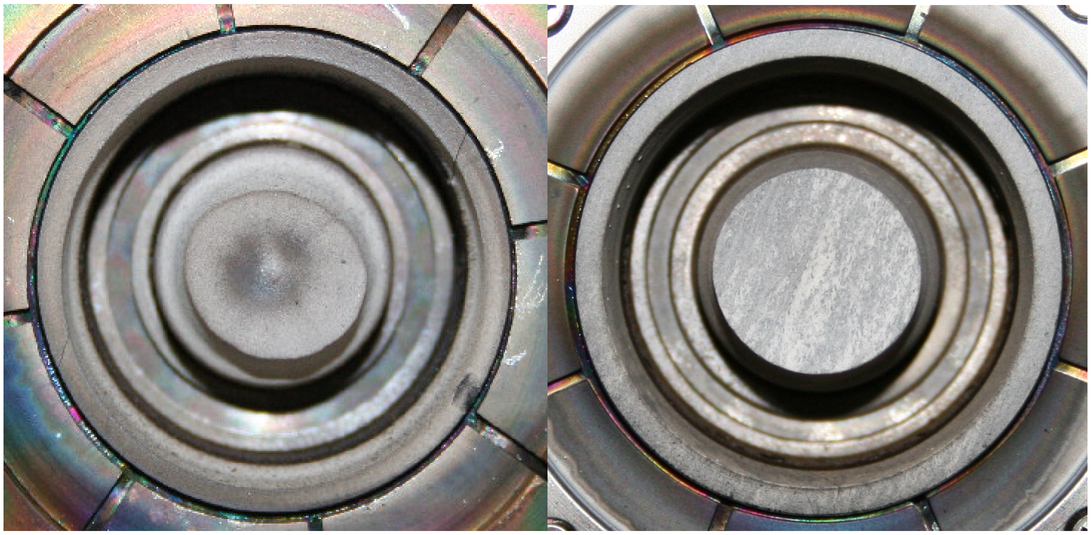


Figure 8. Erosion rate for internal ceramic.



a) **b)**

Figure 9. Picture of HT100 (a) and HT100b (b) after 250 firing hours.

In Figure 9 two pictures of the two thruster ceramics after the same amount of firing time (250 h) are compared; it is evident the difference in the erosion rate for both internal and external walls.

These results indicate that the design modifications made on the new HT-100b with respect to the original HT-100 have produced a drastic reduction in the ceramic erosion rate that means a great increase in thruster lifetime.

B. HT-100b + KhAI cathode

The aim of this test was the validation of the cathode, comprising the anode-cathode ignition characterization and the anode discharge characterization over the entire operative range of the thruster.

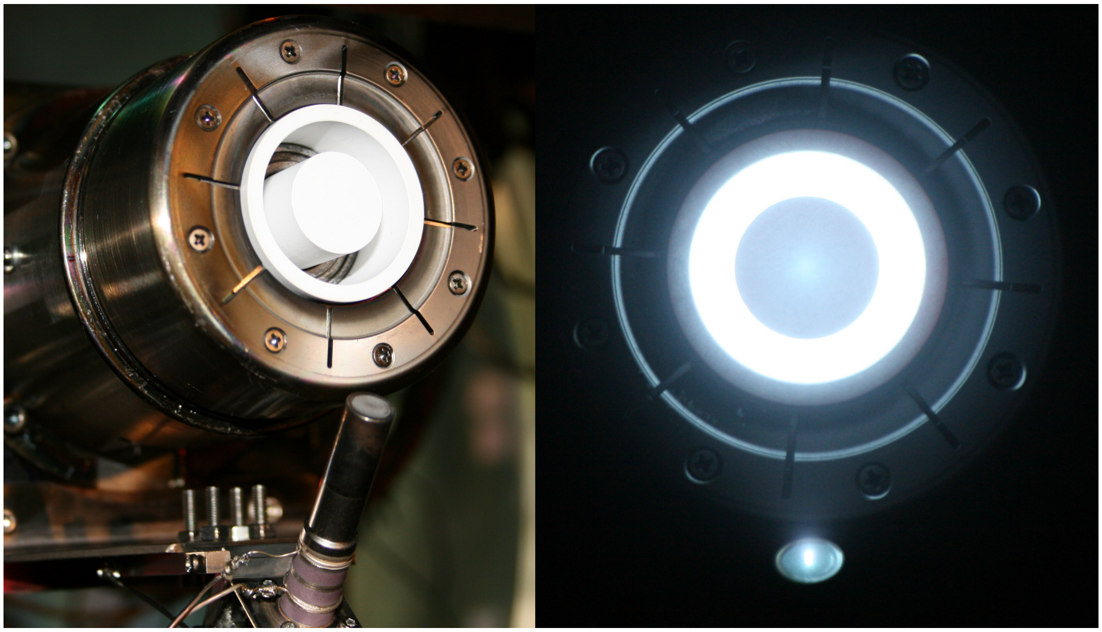
The KhAI cathode, which is developed for space applications, has very low work mass flow rates (0.03-0.12 mg/s) with respect to K&R cathode (1-2 mg/s) and with respect to the anode typical mass flows (0.5-1.25 mg/s). For these reasons the results obtained by this test are very interesting.

During the test, the KhAI cathode was mounted on a dedicated support directly screwed on the balance interface, and the distance of its orifice from the thruster exit and the inclination of its axis with respect to the thruster axis were approximately the same of all the previous test with other cathodes (e.g. K&R and TASI).

The thruster ignition procedure consists in flowing the Xe propellant through the anode and cathode applying the discharge voltage between anode and cathode and finally applying the voltage to the ignition electrode of the cathode. The main (anode-cathode) discharge ignition starts when the voltage is applied to the cathode ignition electrode (ignitor).

From the point of view of main discharge ignition, the thruster has been switched on without any problem using nominal flow rate values (0.75-1 mg/s for the anode and 0.1-0.2 mg/s) and usual discharge voltage values (300 - 350 V). The ignition procedure has been tested for few different cathode and anode operative conditions showing an high thruster ignition repeatability (more than 90%).

From the point of view of anode discharge characterization the KhAI cathode was able to sustain the discharge over a wide range of discharge current (0.45-1 A) and voltage (225-400 V). The cathode reference potential was comprised between -7 V and -5 V revealing a very good cathode coupling with the main discharge. Figure 10 shows HT-100b mounted in the chamber with KhAI cathode before and during the test.



a) b)

Figure 10. The HT-100 b with KhAI cathode before the test (a) and during the test (b)

Unfortunately thruster operation in “spike mode” was never achieved at any operating conditions. The plume, visible in Figure 11 appears diffuse. The “diffuse mode” operation could be due to the inappropriate position of the cathode respect to the thruster. Next tests will be devoted to find the optimal position of KhAI cathode.

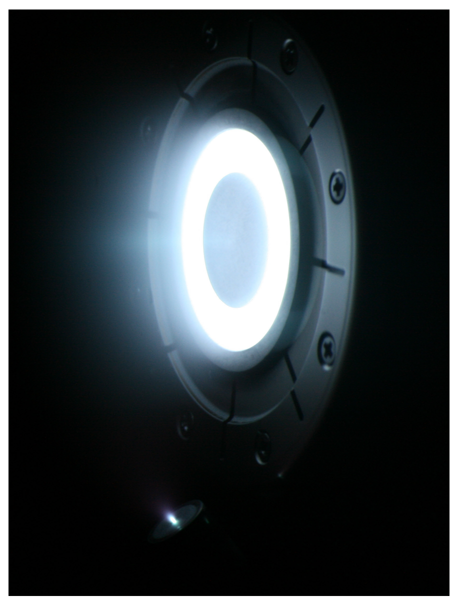


Figure 11. The HT-100b with KhAI cathode during test

C. HT-100c + TASI cathode

The test campaign performed on HT-100c, coupled with TASI cathode, has been performed to obtain a characterization of the thruster.

The results about the power, thrust, specific impulse and thrust efficiency are reported in the figures below (note that specific impulse and thrust efficiency are calculated with only the anode mass flow rate).

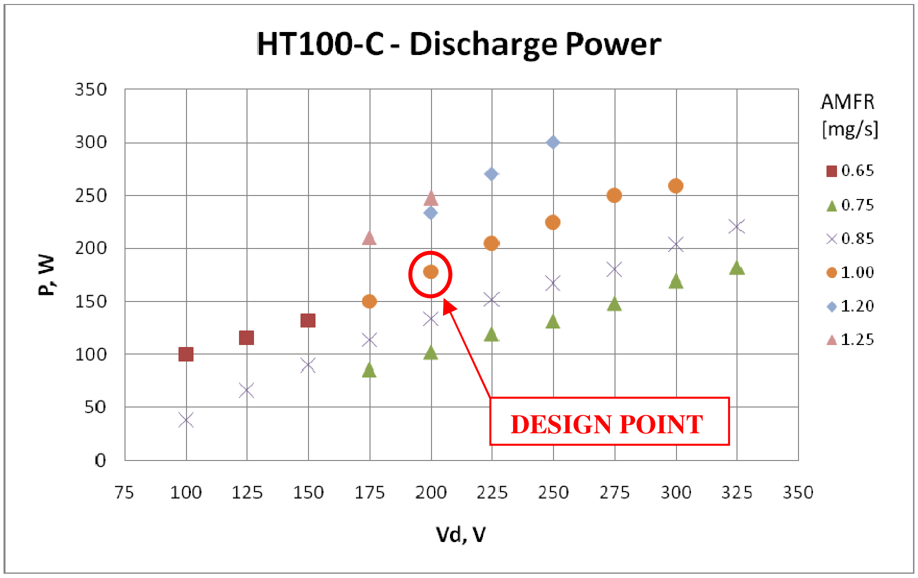


Figure 12. HT-100c characteristics and performances: Discharge Power

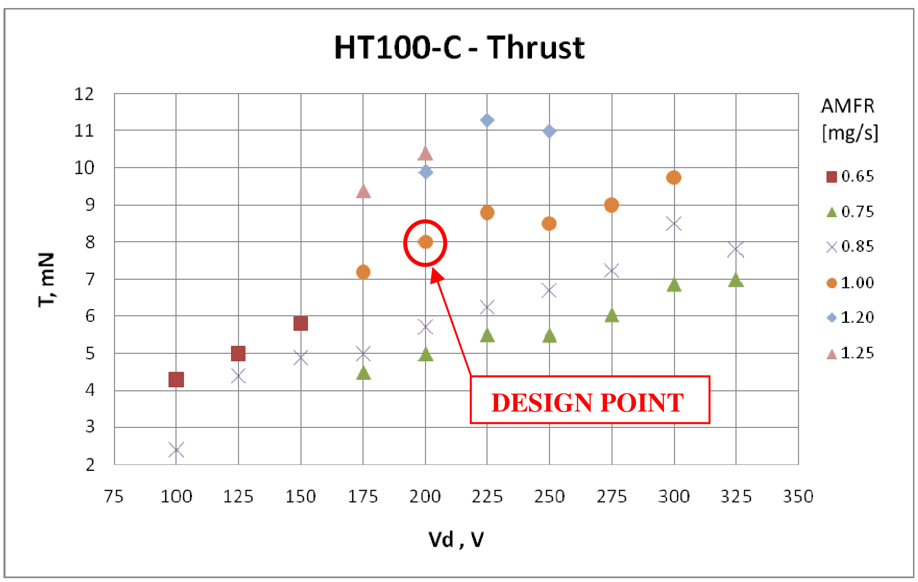


Figure 13. HT-100c characteristics and performances: Thrust

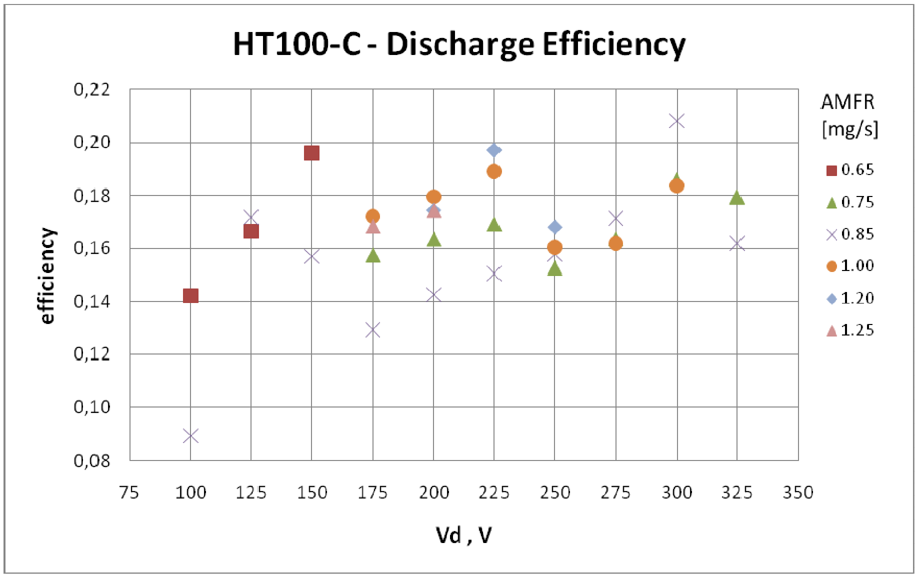


Figure 14. HT-100c characteristics and performances: Discharge Efficiency

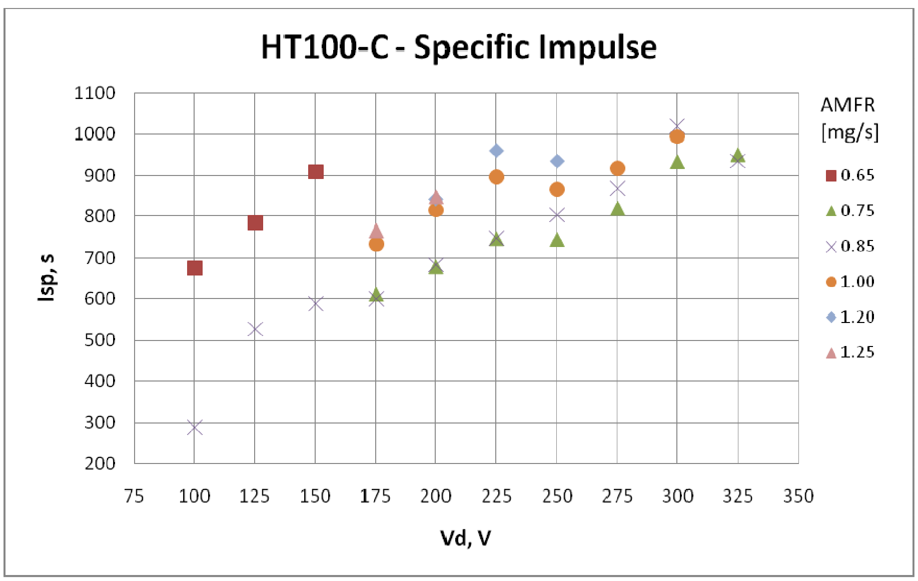


Figure 15. HT-100c characteristics and performances: Specific Impulse

It's possible to note in Figure 12 and in Figure 13 that the value of 8 mN has been reached with a power of about 175 W as expected from the design criteria. The highest thrust of about 11.5 mN has been obtained with an anode mass flow of 1.2 mg/s, a cathode mass flow rate of 0.2 mg/s and a discharge voltage of 225V with a specific impulse near to 1000 s and efficiency of about 20%.

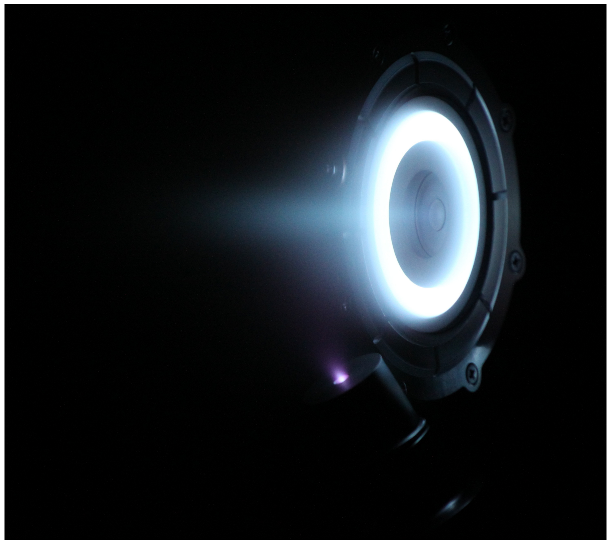


Figure 16. The HT-100c with TASI cathode during test

As Figure 16 shows the spike mode was found. The beam properties were studied using Faraday probes and RPA founding great results mostly for the ionization fraction (in terms of rate between the beam total current collected by Faraday probes and the total discharge current, Ib/Id); in fact the value of the fraction Ib/Id arrived up to almost 60%. In the Figure 17 are represented the Faraday beam current distribution for a typical operating point (discharge voltage 300 V, anode mass flow rate 0.85 mg/s, cathode mass flow rate 0.2 mg/s).

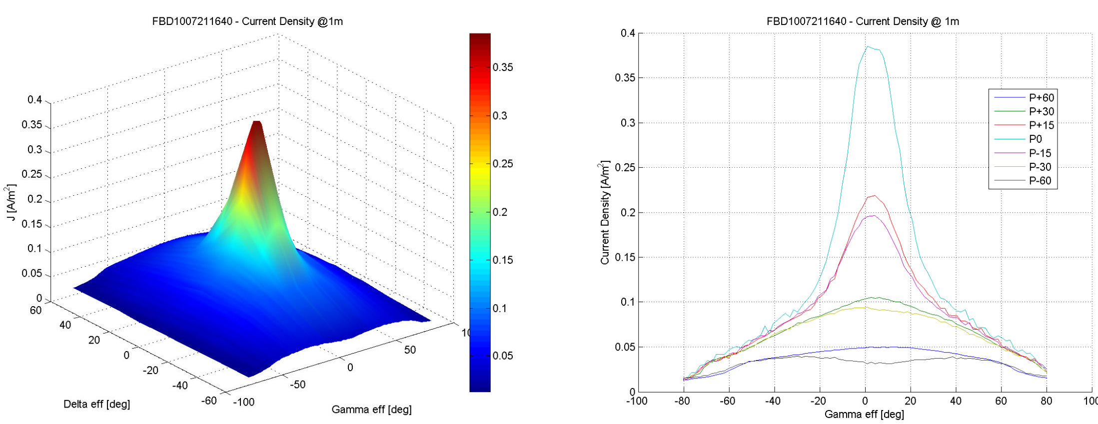


Figure 17. Faraday beam current distribution. Operating parameters: 300 V of discharge voltage,0.85 mg/s of anode mass flow rate and 0.2 mg/s of cathode mass flow rate.

IV. Conclusion

Different low-power (<200 W) thruster models, HT-100b and HT-100c, have been developed and tested by Alta in the last year. All items derive from successful Alta HT-100 design that has reached a quite high development level. Moreover both new models HT-100 (b and c) were tested also with cathode developed for space applications (KhAI and TASI).

HT-100b has a magnetic circuit slightly different than HT-100 in order to reduce thruster ceramic erosion rate and so increasing thruster lifetime. Long firing test campaigns (250 hours of firing) carried out at Alta have shown good results in that direction with a reduction of the erosion rate of about 13% on the inner ceramic wall and of about 10% on the external one. In addition the new model (HT-100b) showed a minor level of erosion even after 450 hours of firing respect to the HT-100 (original model) after 250 hours. The HT-100b with the KhAI cathode has given good results in terms of discharge ignition with high repeatability also with low cathode mass flow rates (0.1-0.2 mg/s) at nominal operating parameters of the thruster (anode mass flow rate (0.75-1 mg/s) and discharge voltage (300-350 V)). The cathode reference potential (-7 V to -5 V) outlined a good coupling between anode and cathode. Unfortunately no spike mode was found.

HT-100c has been scaled up to the nominal point of 175 W and 8 mN. Experimental results confirmed the capacity of this thruster to achieve and work stably at the design point. A larger domain of operating points has been tested to complete the characterization of the thruster. Long firing campaigns will be performed to study the erosion level of the ceramic. The HT-100c model was tested with TASI cathode. The cathode was able to ignite and sustain the discharge in a stable mode for all the tested operating points. The spike mode was found for the most of operational envelope. Next test campaigns will be carried out in order to find the optimal relative position between thruster and cathode.

Acknowledgments

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