

Telemicroscopy and Thermography Diagnostic Systems for Monitoring Hall Effect Thrusters

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Abstract

An advanced diagnostic system has been developed by Alta in the framework of an ESA Technology Research Programme with the aim of investigating erosion phenomena and thermal issues in Hall effect thrusters. This diagnostics is constituted by two different subsystems, one for measuring the erosion of the ceramic channel (Telemicroscopy system), another one for acquiring IR images of the thruster assembly (Thermography system). Both systems have been recently tested in a dedicated experimental campaign, using Alta's HT-100 as target thruster. Channel erosion and temperature distribution have been measured for two non conventional ceramic materials (Macor and Shapal, each of them operated for 70 hrs) and for a Boron Nitride insulator.

I. Introduction

Hall effect thrusters are among the most effective devices for a wide number of space applications, ranging from Atmospheric drag compensation (with low power HETs), to orbit raising or interplanetary travel. For this reason, extensive experimental campaigns are continuously carried out in order to design thrusters that are more and more efficient and reliable. Two focal issues are the erosion of the ceramic channel and the thermal control of the thruster assembly. Both issues are especially harsh when it comes to deal with small size HETs.

Channel wall erosion is the phenomenon which limits HETs lifetime. Thus, a better understanding of this phenomenon is necessary to design devices able to operate successfully for thousands of hours, as requested by almost every mission involving low-thrust electric propulsion. Several theoretical models have been developed in

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recent years for studying plasma behaviour inside the acceleration channel and predicting channel erosion^{1,2,3,4}. However, it is necessary to integrate such models with experimental data in order to check and validate the theoretical results. A comparison with experimental data is essential to refine such models and improve their overall accuracy. Unfortunately, only a few complete set of data are available in literature for a comparison^{5,6}.

Thermal control becomes a critical issue when HETs are scaled down in size, because it is difficult to dissipate the heat released to the walls by the hot plasma flowing through the channel. Ceramic temperatures exceeding 600-700°C are pretty common (this is true also for large, high-power thrusters) and the whole thruster assembly must be carefully monitored in order to avoid major failures of some component^{7,8}.

A new diagnostic system has been developed by Alta^{9,10} (in the framework of an ESA Technology Research Programme) which is capable of detecting the erosion of the ceramic channel and of monitoring the temperature of the thruster assembly. The diagnostics is constituted by two separate subsystems, a telemicroscopy system to optically measure ceramic erosion and a thermography system to acquire IR images of the thruster and monitoring its temperature. Both systems operate in vacuum and are directly installed inside the vacuum facility, allowing us to collect data with no need of interrupting the experiment, opening the chamber and unmounting the thruster from its balance. The whole system has been recently tested in Alta's premises, in order to assess its capabilities. Alta's HT-100 mini Hall thruster has been adopted as target device and three different ceramic materials have been successively installed and operated.

The present paper starts with the description of the diagnostic systems (paragraphs II and III), followed by a short section dedicated to test setup and system calibration (section IV). In the last section (par. V) test results are illustrated and discussed, highlighting the achievements of this new diagnostic system and suggesting possible future developments to make it even more effective and flexible.

II. Telemicroscopy System

The telemicroscopy system (fig. 1) consists of a moving arm carrying an optical head with two cameras (to acquire images of the ceramic channel profile) and two lasers (to illuminate the edges of the ceramic channel). The diagnostics is non-intrusive and it can be installed inside the vacuum chamber. This allows measuring the erosion of the acceleration channel with no need of opening the facility, thus saving a great deal of time (and costs) when multiple measurements have to be taken. The supporting structure includes a translational platform on which a rotational stage is mounted. Both mechanisms serve to position the optical system out of range of the ion beam plume during thruster firing (parking position). The translation stage and the rotation stage are controlled by vacuum compatible stepper motors. Four microswitches are placed at the operating and parking position of the diagnostics to ensure accurate alignment of the optical head with the target.

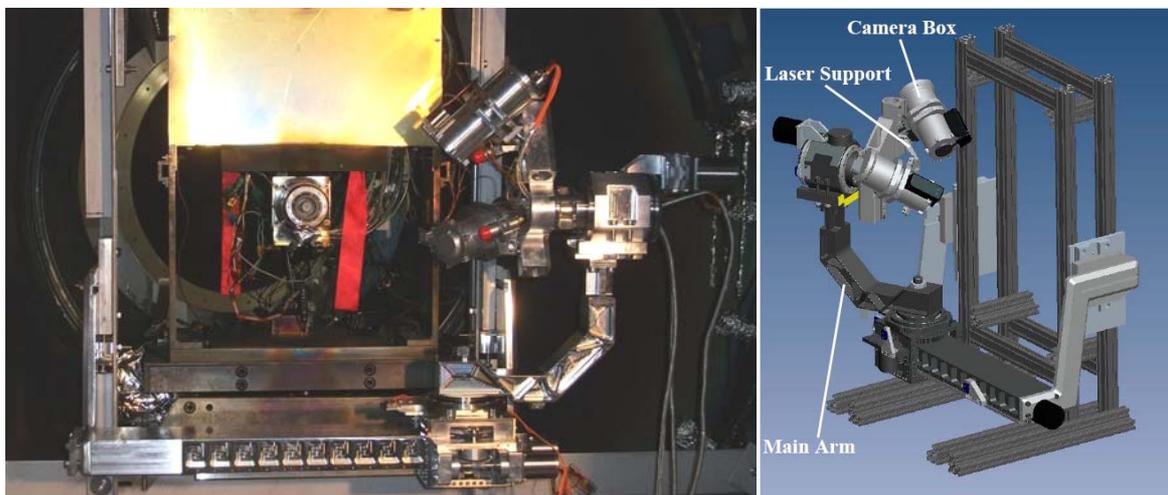


Fig. 1: Telemicroscopy system in HET configuration

The erosion is measured through a 3D reconstruction of the channel profile. Reconstructing of the profile is performed starting from the images acquired by the cameras. Such images show the projection of a laser line on the channel edges (that is the reason why there are two lasers and two cameras; one is for the inner wall of the channel, the other for the outer wall). The variation of the channel shape can be obtained by observing how the shape of the laser line changes in time when the channel starts to be eroded (see fig.2).

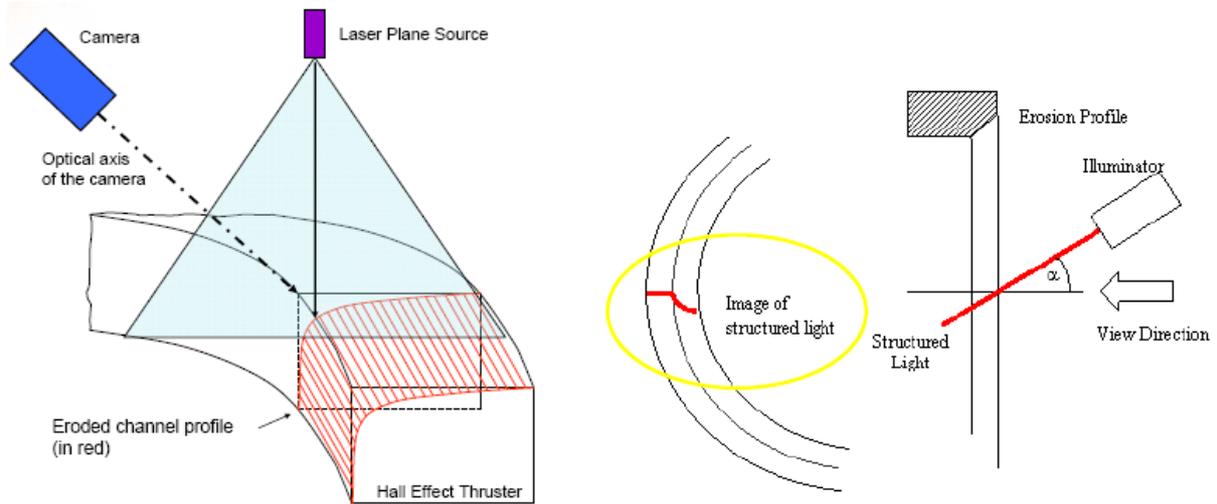


Fig. 2: Working principle of the telemicroscopy diagnostic system for 3D image reconstruction

Each camera is protected by a steel enclosure, hosting a pressure sensor, the focus mechanism and the lens assembly as well. The cylindrical boxes provide suitable operation conditions and screen the cameras from sputtering during firing. A DA15M feedthrough for the electrical connections is placed on the rear flange of the box. Each lens is protected by a shutter that is actuated by a small stepper motor. The focus mechanism is operated by a linear actuator which moves the camera back and forth in order to obtain optimal image quality. A scheme of a camera box is represented in fig. 3.

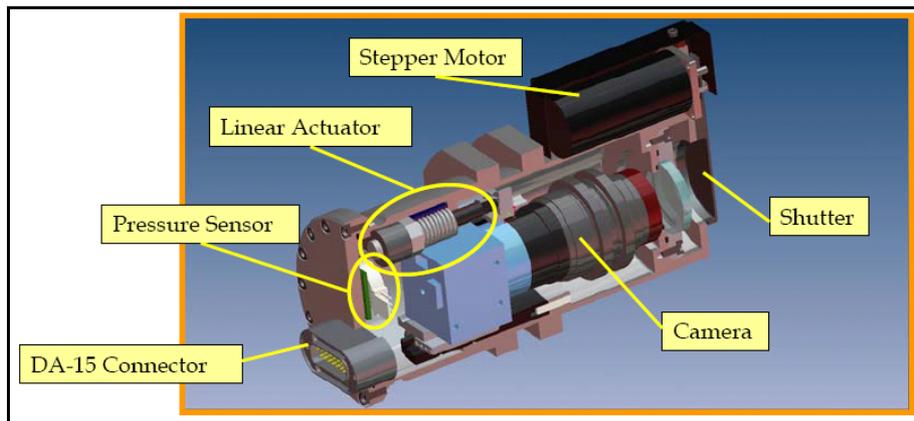


Fig. 3: Detail of the camera box

III. Thermography System

The core of the thermography system consists of an infrared camera, which is placed inside the vacuum facility in order to have an optimal view of the thruster assembly and which operates in a wide range of temperatures (between 0°C and 800°C; for future applications, if necessary, this range can be shifted towards higher temperatures, reaching a limit of about 1200°C).

A cylindrical metal box (fig. 4) encloses the IR camera and a pressure sensor to ensure proper operation conditions, as the camera is not vacuum compatible. A DB25M connector for power supply and signal input and output is mounted on the rear flange of the protecting box. Inside the box (fig. 5), a brushed electric motor controls the focusing of the camera lens. The focus has to be regulated only at the start of the testing phase since the distance between the camera and the thruster is constant throughout the test. An aluminium shutter, operated by a UHV-compatible stepper motor, protects the germanium IR window during thruster firing. Two heaters can be installed inside the box in case the thermography system is operated in thermo-vacuum conditions.

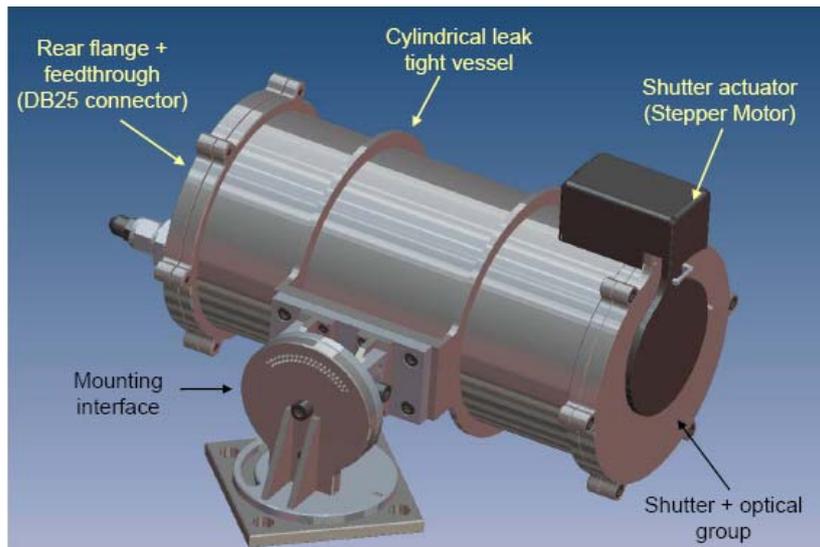


Fig. 4: IR Camera box – external view

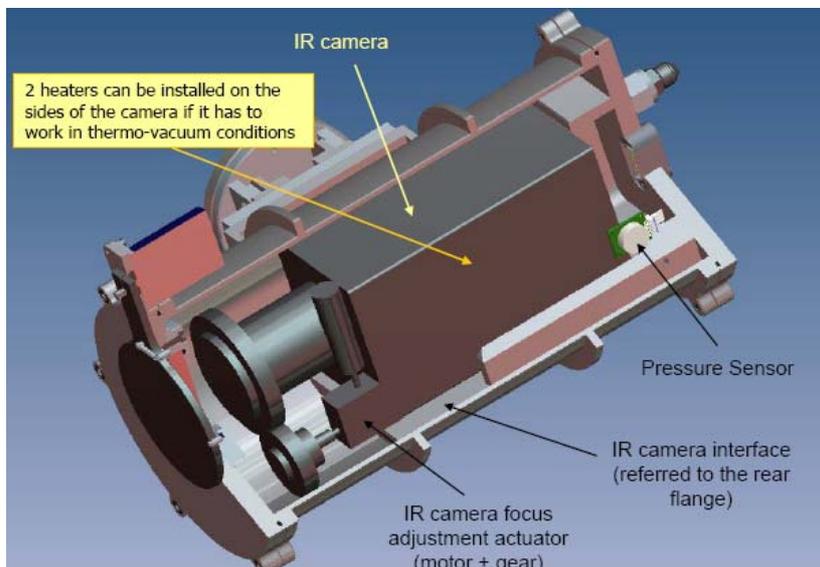


Fig. 5: IR Camera box – internal view

The thermography assembly is placed outside the ion beam plume at a fixed position, preferably at an angle of 45° with respect to the thruster exit.

IV. Test Setup

The experiments have been carried out in the IV-4 vacuum chamber with Alta's HT-100 Hall thruster. The electronics and the software used to calibrate the system, to acquire the images and to process the results have been developed specifically for the presented diagnostics.

A. Vacuum Facility

The IV-4 facility consists of two vessels built out of austenitic stainless steel AISI 316 L with a low permeability ($\mu_r < 1.06$). The Main Chamber serves as the beam expansion volume and is connected to the smaller Service Chamber through a gate valve, which can separate the thruster setup from the main chamber in case of emergency or maintenance operations. The dimensions of the chamber are reported in Table 1.

The thruster and thrust balance are installed in the service



Fig. 6: Alta's IV-4 vacuum facility

chamber, which accommodates as well the connections for the propellant feeding and power supply.

To damp the beam energy and to reduce contamination of the thruster due to back sputtering, a bi-conical water-cooled beam target, lined with Grafoil, is mounted at the rear of the vacuum chamber, i.e. the end of the main vessel in front of the thruster. The conical shape directs the sputtered atoms towards the cold heads at the side walls.

	<i>Length</i>	<i>Diameter</i>
Main Chamber	2500 mm	2000 mm
Service Chamber	1000 mm	1000 mm
Gate Valve	-	1000 mm
Total chamber length	4200 mm	-

Table 1: IV-4 Vacuum Chamber, relevant sizes

Completing the vacuum procedure is done by three pumping stages:

- Primary stage: 2 scrolls @ 25 m³/hr each
- Turbo stage: 1 turbo @ 1500 l/s; 1 scroll @ 25 m³/hr
- Cryo pump: 5000 l/s

A fourth stage consists of six cold heads with a pumping rate of 70000 l/s, thereby lowering the chamber pressure to an ultimate value of 10⁻⁸ mbar and maintaining a pressure in the order of 10⁻⁵ mbar during thruster operation. The total vacuum procedure takes 12 to 24 hrs.

B. Target Thruster

The HT-100 is an SPT type of Hall thruster entirely developed by Alta and operating with a nominal power of 100 W. The thruster has been operated at a higher power level (between 150 and 160 W where feasible) in order to enhance the erosion phenomenon. The performance specifications of the test thruster are displayed in Table 2.



Fig. 7: Alta's HT-100 mini Hall thruster

<i>HT-100</i>	
Mass	900 g
Dimensions	Ø 70 x 35 mm
Propellant	Xenon
Thrust	5.1 mN
Specific impulse	1083 s
Efficiency	17.4%
Operated Power	156 W
PPU power input	unregulated 28 V, 2.5 A (peak)
PPU output	150-400 V, 0.15-1.5 A

Table 2: HT-100 Technical Specifications

C. Electronics and Software

The telemicroscopy diagnostics is connected to the control rack through the vacuum chamber feedthroughs by means of D-sub connectors. The PC that controls all devices is linked up to the control rack by a LAN cable. The cameras are not connected to the control rack, but directly to the PC via USB cables. The positioning system and the optical head are fully actuated by using Labview software. In order to position the cameras as required, an algorithm with a fixed amount of motor steps is programmed to place the optical head in the same parking and operating position after each series of measurements. The same is done to ensure full opening and closure of the shutters. The

Labview software furthermore contains the program to acquire the images. A MATLAB-based program then elaborates the acquired images from which it reconstructs the channel profile.

The termography system is governed through a separate rack and a dedicated PC unit, connected via LAN cable. A customized software has been developed to acquire and then elaborate IR images of the target thruster. From the same control panel adopted for image acquisition it is also possible to control the internal pressure of the camera box, to open/close the shutter and to focus the camera.

D. Telemicroscopy System Calibration

The Telemicroscopy system has been calibrated to acquire the erosion data relative to a HT-100 Hall Effect Thruster. The system calibration is necessary to define the exact position of the laser plane with respect to the camera and to set the focusing parameters of the camera. Fig. 8 shows the target grid that has been employed to calibrate the system, here mounted on a micrometric translation stage.

To calibrate the system, five pairs of images are taken. Each pair includes an illuminated picture of solely the target grid and a darker picture of the grid marked by the laser light (see fig. 9). After each acquisition of a pair of images, the target grid is shifted away from the camera by 0.5 mm. From these images the position of the plane of the laser line with respect to the camera is obtained.

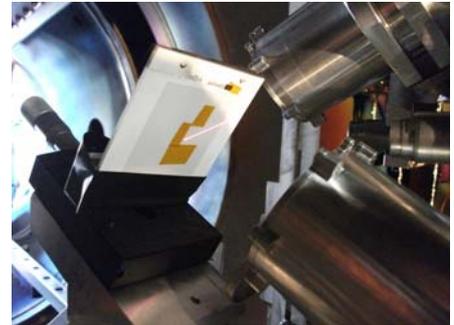


Fig. 8: Telemicroscopy system calibration

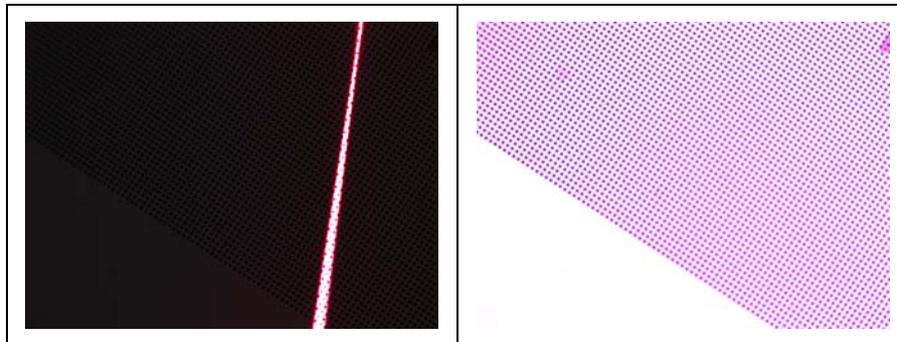


Fig. 9: Grid images for system calibration – dark grid with the laser turned on (left), illuminated grid (right)

E. Thermography System Calibration

The infrared camera has to be properly calibrated in order to: a) take into account the presence of another germanium lens in the box which protects the camera itself from the vacuum environment; b) compensate for the different emissivity values of the materials involved in the temperature measurement.

The presence of another germanium lens can be easily taken into account by tuning the IR software settings (because they allow the user to set a value variable between 0.01 and 1 as a “transmission coefficient”). However, tests carried out on a body of a known emissivity showed that the presence of a lens like the one we used in this experiment negligibly affects temperature measurements.

To have realistic measurements of the channel temperature, the emissivity of the employed ceramic materials has to be known. To evaluate such emissivities, a simple setup has been arranged. Before installing it in the thruster, each ceramic channel has been connected to a thermocouple, protected with a box by external reflections and heated with a halogen lamp. Then its temperature has been monitored both with the thermocouple and the infrared camera, in order to determine the emissivity of the material at the beginning of life. The same measurement has been carried out after the completion of the experimental campaign, to see how the deposition of sputtered graphite from the chamber walls affected the value of the ceramic emissivity. Results are displayed in Table 3.

Emissivities of ceramic materials		
Material:	Emissivity BOL:	Emissivity EOL: ⁽¹⁾
Shapal	0.83	~1
Macor	0.87	~1
BN	0.90	~1

Table 3: Emissivity of ceramic materials employed in the present experiment

After several hours of operation a certain amount of graphite (sputtered from the vacuum chamber walls) deposited on the ceramic surface and increased its emissivity to a value very close to 1. Although graphite distribution is not perfectly uniform, assuming $\epsilon=1$ at the EOL turns out to be a good approximation.

V. Test Results

The experimental campaign consisted of three successive test sessions where HT-100 has been operated with three different ceramic materials, Boron Nitride, Macor and Shapal respectively.

With Boron Nitride insulator, the telemicroscopy diagnostic system has been used to measure the erosion on a channel that already underwent a series of previous tests unrelated with the present one. The erosion has then been measured after 450 hrs of operation, before unmounting the thruster from its stand. This first test does not give any hint about the erosion rate (since it consists of a single measurement in time), but it shows the capability of the laser source to properly work on a surface which is almost completely covered with backsputtered graphite.

Then, brand new Macor and Shapal ceramic channels have been installed on the thruster and their erosion has been measured in both cases after 35 and 70 hrs of operation.

Since the diagnostic system has the capability of capturing the erosion on different azimuthal sections of a target thruster, for each channel the erosion has been measured on four azimuthal stations shifted of 90° (see Fig. 10) and called North, East, West and South for the sake of simplicity. This multiple measurement provides meaningful information about the axial symmetry of the erosion pattern.

Although the telemicroscopy system has been designed and assembled for observing the erosion on both profiles of the channel (inner and outer), a failure of one of the two cameras experienced shortly after the beginning of the experiment prevented measurements to be taken on the outer edge. Unfortunately, the camera could not be fixed before the closure of the experimental campaign, thus only images relative to the inner ceramic edge have been taken and processed with the software to detect the profile erosion.

The thermography system has been continually activated throughout the series of tests, in order to monitor the temperature of the ceramic channel and of the thruster assembly in general. As expected, remarkable differences have been found in the thermal behaviour of the three ceramics adopted along the experiment.

By using the IR camera a thermal transient analysis has been performed as well, with the purpose of understanding how fast thermal steady conditions were attained starting from thruster ignition.

A. Boron Nitride Channel – Telemicroscopy Measurement of Erosion

Images of the laser line projected on the inner edge of a BN channel after 450 hrs of operation are presented Fig. 11 in These two pictures are relative to the northern azimuthal section of the thruster and they clearly show the lowering of the inner edge (thus the shrinking of the inner ceramic radius) due to erosion. Channel profiles (up to 6-7 mm inwards from the tip) have then been reconstructed via software for all the four sections investigated and are displayed in Fig. 12. Fig. 13 shows the BN insulator after it has been removed from the thruster: backsputtered graphite has covered its entire surface making it dark grey.



Fig. 11: Laser light projected on the inner edge of BN channel – at the beginning of life (left), after 450h (right)

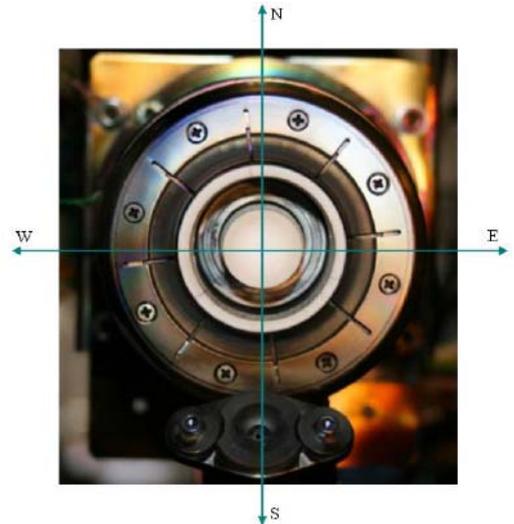


Fig. 10: Four azimuthal sections where the erosion is measured (North-East-South-West)

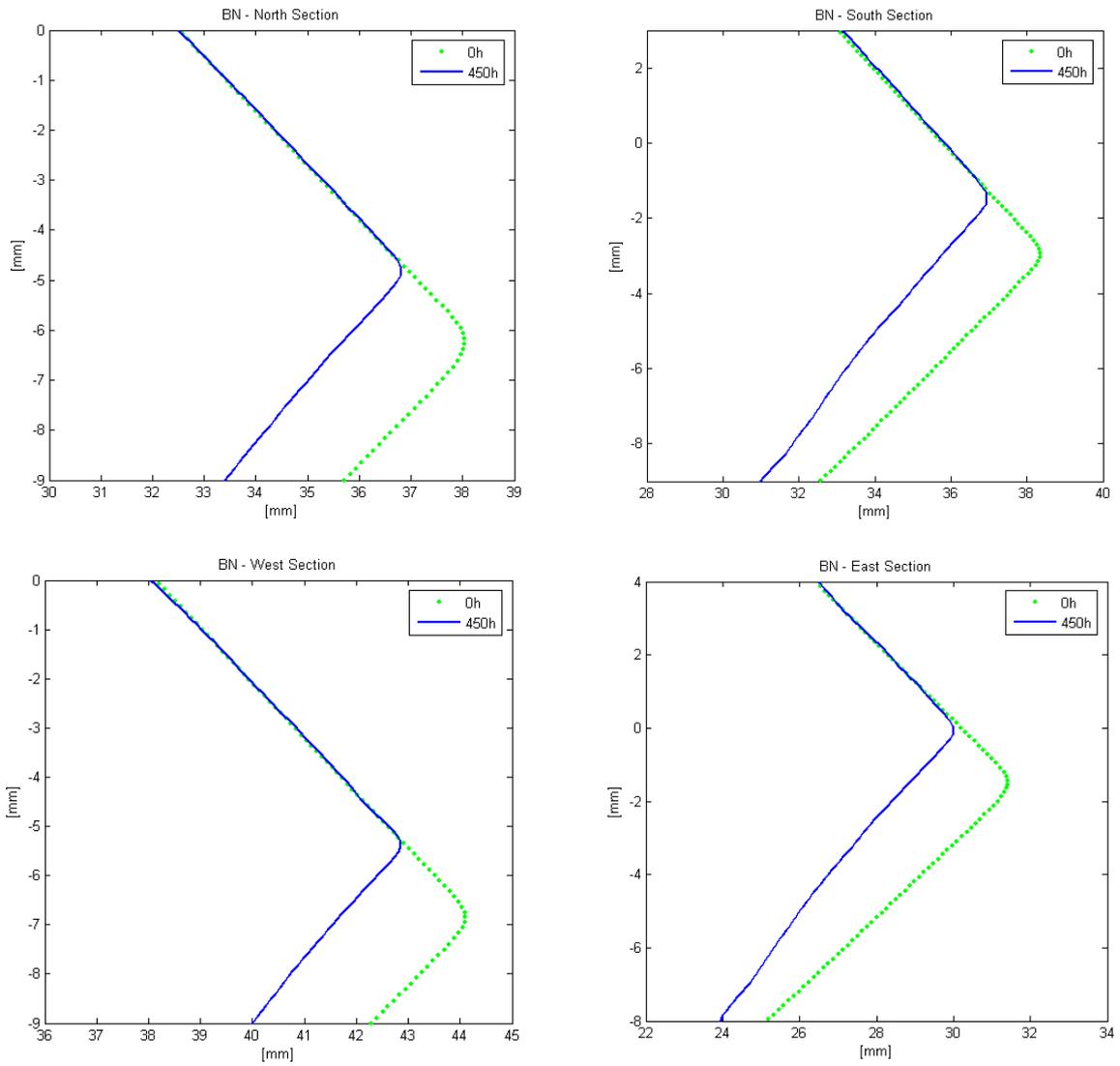


Fig. 12: Reconstruction of BN channel profiles at four different azimuthal positions



Fig. 13: BN ceramic channel after 450 hrs of operation

B. Macor Channel– Telemicroscopy Measurement of Erosion

Macor is a glass ceramic with a high thermal shock resistance and a low thermal expansion coefficient. Its electric and thermal properties are reported in Table 4.

<i>Macor Properties</i>	
Density [Kg/m ³]	2520
Maximum operating temperature [°C]	>800
Resistivity @ 25°C [ohm.cm]	>10 ¹⁶
Thermal Conductivity [W/m/K]	1.46

Table 4: Macor properties

To evaluate the insulator deterioration, pictures have been taken at BOL and after 35 and 70 hours of firing at a power level of 160 W. Fig. 14 shows the acquired images of the channel exit marked by the laser. Fig. 15 shows the profile reconstruction from which the erosion can be immediately determined. After 70 hrs, ceramic erosion is 0.78 mm at the channel tip.

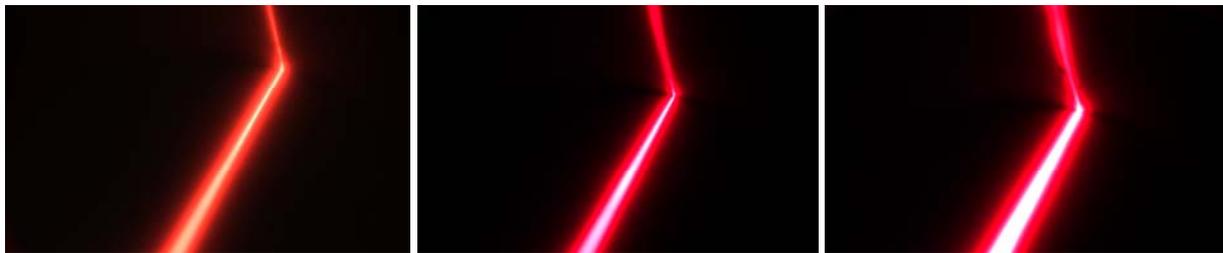


Fig. 14: Camera images of Macor channel inner profile at BOL (left) and after 35h (center) and 70h of operation (right)

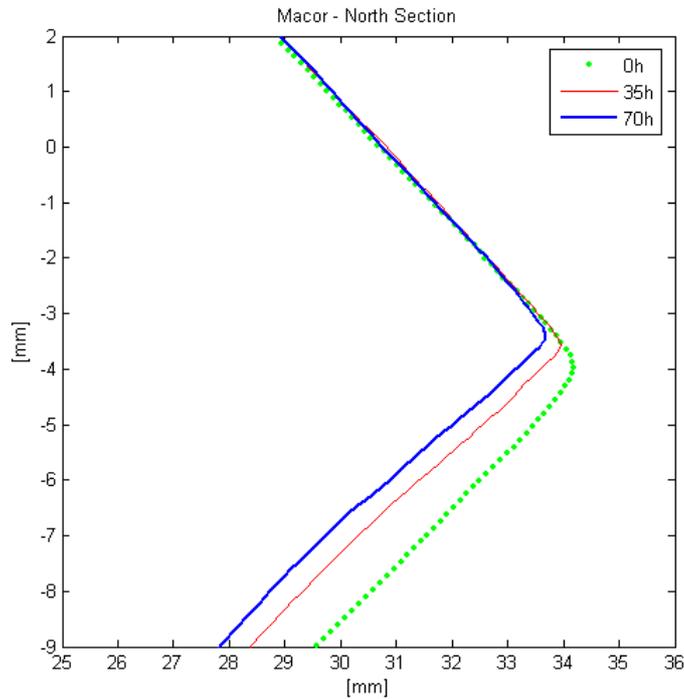


Fig. 15: Reconstruction of eroded profile for HT-100 thruster firing with Macor insulator

C. Shapal Channel– Telemicroscopy Measurement of Erosion

During the third firing session a Shapal ceramic channel was installed on the HT-100 thruster. Shapal is a ceramic material which has the peculiarity of being a good thermal conductor as well as an effective electrical insulator. Its main properties are displayed in Table 5.

<i>Shapal Properties</i>	
Density [Kg/m ³]	2900
Maximum operating temperature [°C]	>1900 (in non-oxidizing atmosphere)
Resistivity @ 25°C [ohm.cm]	>10 ¹²
Thermal Conductivity [W/m/K]	90

Table 5: Shapal properties

Again, images have been taken before thruster operation and after 35 and 70 hours of firing with a power input of 110 W. A profile reconstruction is shown in Fig. 16. The difference between the profile before the beginning of thruster operation and the profile after 70 hours of testing, is hardly noticeable. After a firing period of 70 hours, 0.10 mm of insulator have been eroded at the channel tip. This is a significantly lower value than the one found for Macor and Boron Nitride. One of the reasons of this behavior is connected with Shapal high thermal conductivity. Since Shapal is a good thermal conductor, when it is used as a channel insulator it is not possible to operate the thruster at a power exceeding 100-110W in order not to overheat other parts of the thruster assembly. Working at a lower power (and then at a lower applied potential) the erosion turns out to be greatly reduced.

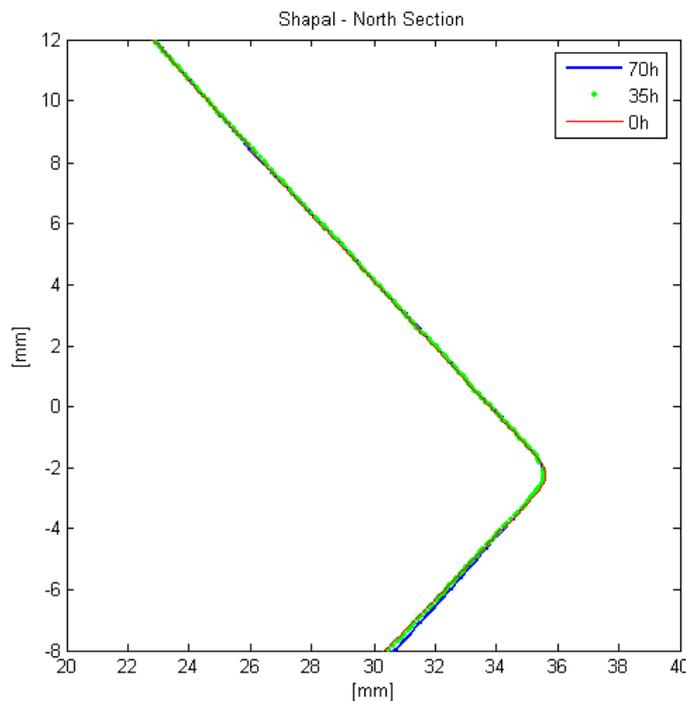


Fig. 16: Reconstruction of Shapal eroded profile

D. Comparison between Telemicroscopy and Caliper Erosion Measurements

To validate the data collected with the telemicroscopy system, all the channels have been measured with a caliper after having been extracted from the thruster. This is a partial validation, because it is only possible to compare the erosion of the diameter at the tip of the channel. However, results obtained with image processing turned out to be pretty accurate when compared to caliper measurements, as can be seen in Table 6 and Table 7 below.

Material	Hours of operation	Calliper measurement (North-South)	Telemicroscopy measurement (North)	Telemicroscopy measurement (South)
Boron Nitride	450	3.88 mm	1.89 mm	2.06 mm
Macor	70	1.54 mm	0,78 mm	0,79 mm
Shapal	70	0.14 mm	0,09 mm	0,08 mm

Table 6: Erosion measurements – North & South azimuthal stations

Material	Hours of operation	Calliper measurement (East-West)	Telemicroscopy measurement (East)	Telemicroscopy measurement (West)
Boron Nitride	450	4.14 mm	2,09 mm	1,99 mm
Macor	70	1.64 mm	0,85 mm	0,81 mm
Shapal	70	0.20 mm	0,11 mm	0,10 mm

Table 7: Erosion measurements – East & West azimuthal stations

E. Temperature Measurements with the Thermography System

Here follows a series of pictures displaying the temperature distribution for the three different channel-wall materials that have been tested: BN, Macor and Shapal. All the pictures have been taken at the thermal steady state. The power level is not the same everywhere, because it was not possible to operate the Shapal channel at the same power of the others due to thermal restrictions (Shapal is a good thermal conductor and, as a consequence, the thruster supporting structure becomes too hot if the operative power is raised over a threshold level).

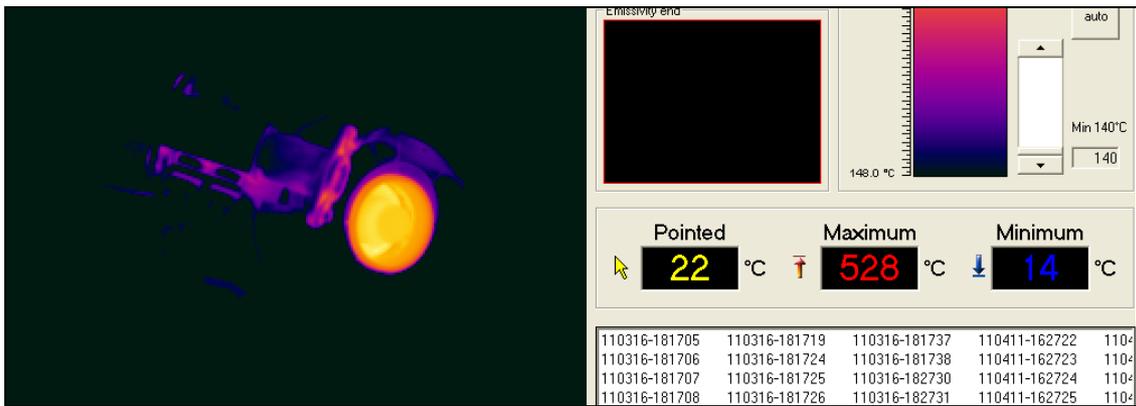


Fig. 17: Boron Nitride ceramic, steady-state, power =160W – Max channel temperature = 528°C

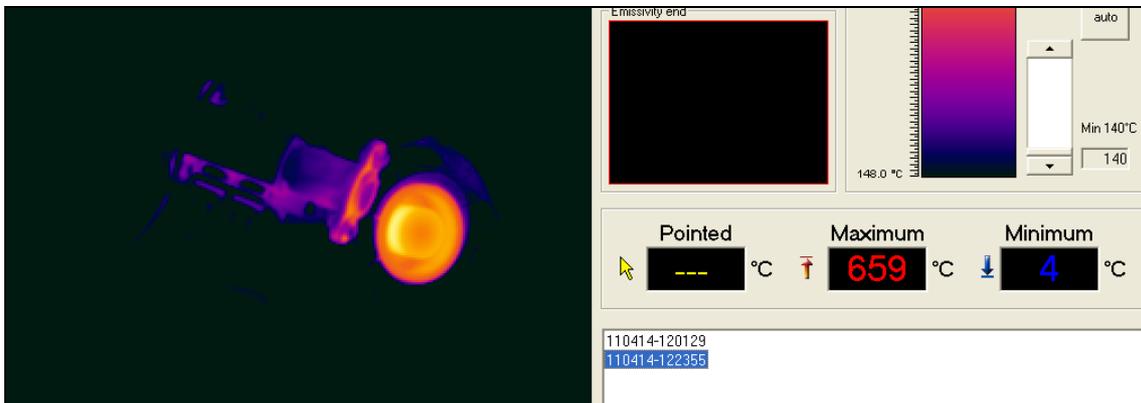


Fig. 18: Macor ceramic, steady-state, power=160W – Max channel temperature = 659°C

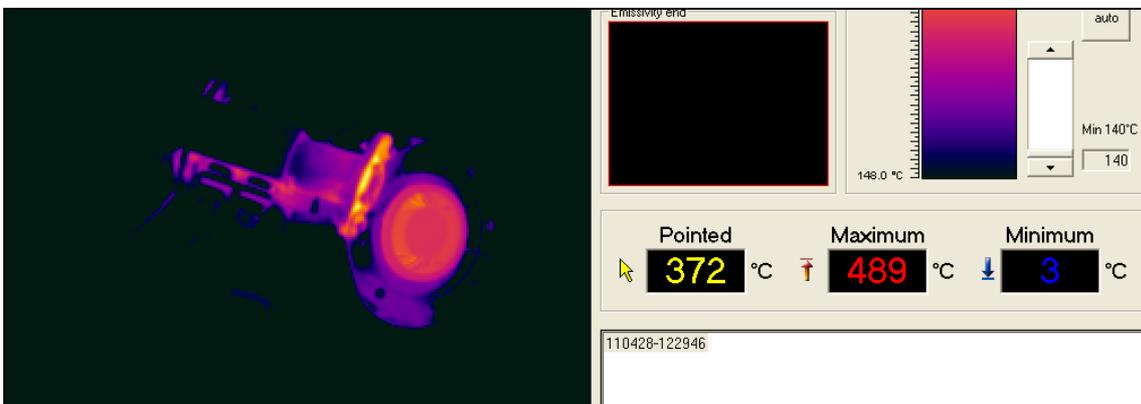


Fig. 19: Shapal ceramic, steady-state, power=110W – Max channel temperature = 372°C

Shapal, being the best thermal conductor among the three materials tested, shows a peak temperature which is considerably lower than the other two (although also the operating power level is lower). On the contrary with Macor, which is an excellent thermal insulator, the heat is trapped in the ceramic walls and the peak temperature exceeds the one reached using Boron Nitride by more than 100°C. These measurements confirm that BN is probably the best choice for this application, since it is the best trade-off between a strong thermal insulator (which prevents the other parts of the thruster from an excessive heating, but leads to a higher channel temperature) and a poor thermal insulator (which does not protect the rest of the thruster, but significantly decreases the peak temperature at the channel tip).

F. Thermal Transient Analysis with the Thermography System

The infrared camera can be usefully exploited to check how long it takes to all the main thruster components to reach a steady temperature after the thruster is turned on.

Several pictures taken at different instants are reported here for Alta’s HT-100 thruster operated with a Macor ceramic channel (see Fig. 20) and fed at a power level of 70W. Stationary conditions have been reached after about 30 minutes, as it can be seen from the diagram in Fig. 21.

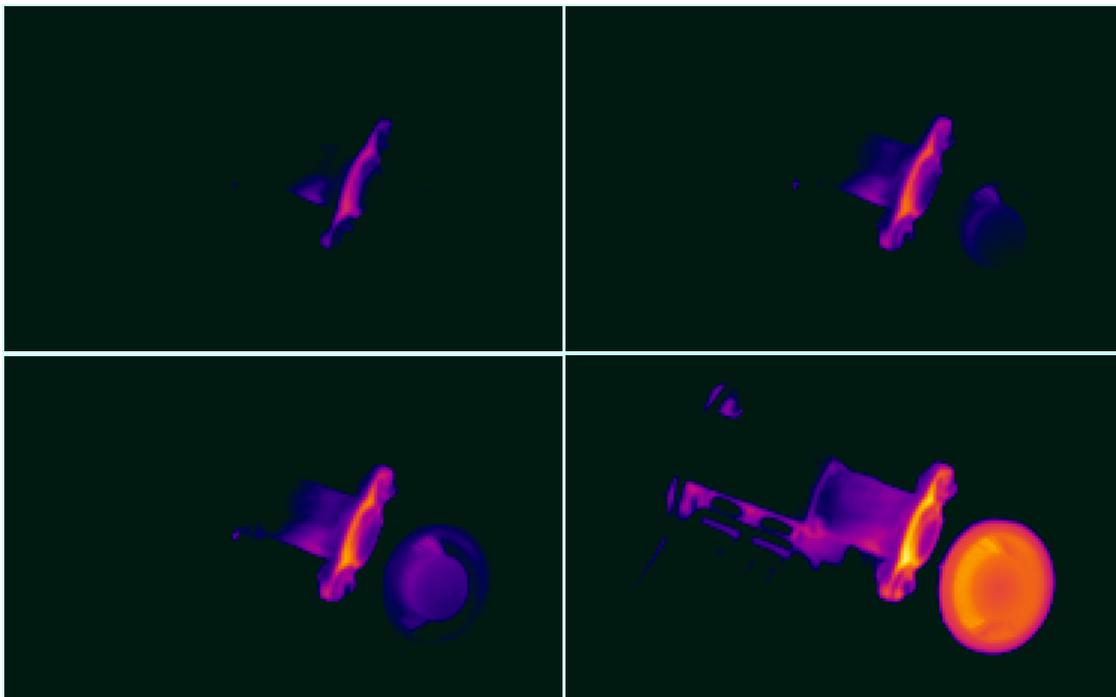


Fig. 20: Four successive images of HT-100 taken at different times during the first thirty minutes of operation

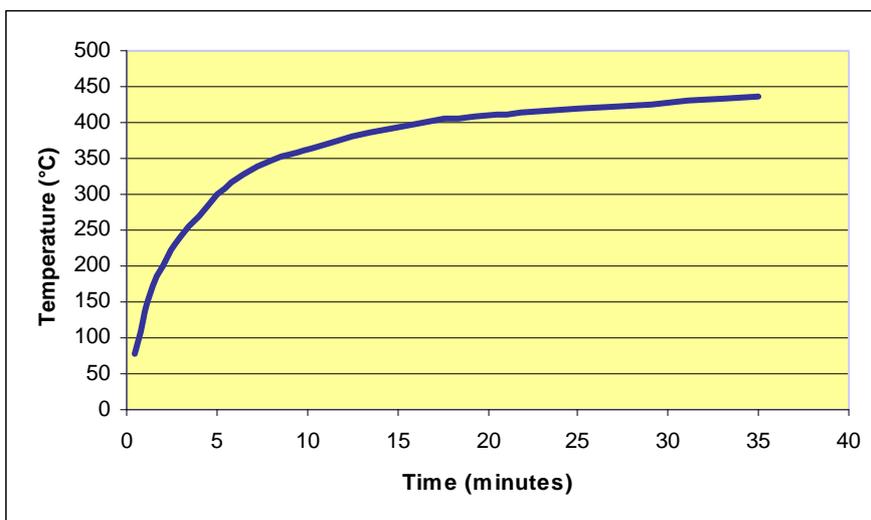


Fig. 21: Macor Max. Temperature vs Time

The maximum temperature reached on the channel walls during the thermal transient test was slightly lower than 450°C. It is interesting to compare this result to the one obtained with the thruster working at a power level of 160W, where the maximum temperature detected in the channel was of 659°C. Halving the power level, the channel temperature has been reduced of more than 200°C.

VI. Conclusions

An extensive experimental campaign has been carried out in Alta to assess the capabilities of a newly developed diagnostic system, intended to measure channel erosion and temperature distribution in Hall effect thrusters. The diagnostics consists of two separate subsystems: the telemicroscopy system, which fulfills the task of optically measuring the channel erosion, and the thermography system, which is used to monitor the temperature of the thruster assembly. Tests with three different ceramic materials have been carried out, always using Alta's HT-100 as target thruster. The diagnostics turned out to work effectively and it measured with good accuracy both the ceramic erosion and its temperature during thruster operation. Besides, the system successfully worked in a UHV environment for several hundred hours, with no need of maintenance and without any failure of the multiple mechanisms involved. The experiment also highlighted remarkable differences in the behaviour of the adopted ceramic materials. Boron nitride turned out to be the best trade-off in terms of thermal conductivity, while Macor tended to trap the heat released by the plasma within the channel walls, raising up their temperature. The configuration with Shapal channel instead overheated in the region of the backplate, being Shapal a good thermal conductor. For what concerns the erosion, Shapal channel is the one showing a lower erosion rate, although it must be noted that it was operated at a lower power level due to thermal problems.

Future plans are to test the system on other HETs to further validate its capability of capturing channel erosion and operating temperatures. To improve the versatility of the telemicroscopy system, the supporting structure could be upgraded so that the system can be readily interfaced with larger facilities (such as Alta's IV-10 vacuum chamber) and used on high-power thrusters. The thermography system can be equipped with a different IR camera to extend its range of measurement to higher temperatures and, in a refined version, it could be mounted on a movable support in order to view the thruster assembly from different angles.

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