Characterisation of a 20 kW Dual Channel HT with Different Propellants (Xe/Kr/Ar)

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Abstract: A 20 kW class Hall Thruster featuring two coaxial channels has been designed at the University of Pisa and manufactured by Aerospazio Tecnologie. The thruster was preliminarily characterized in 2024 in the framework of the ESA TANDEM program. The following paper outlines the findings from the recent characterization test campaign performed on the TANDEM thruster coupled with the new cathode developed within the CHEOPS-VHP-BB program. This test was carried out at AEROSPAZIO Tecnologie in 2025 in the LVTF-3 test facility. The TANDEM thruster was operated with three different propellants (Xenon, Krypton, and Argon) in four operating points (from 4.5 to 20 kW) at discharge voltages of 300 and 400 V. Thermal assessments were performed using an infrared thermal camera. This document presents the experimental results collected throughout the testing.

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Nomenclature

AEPD	=	Advanced Electric Propulsion Diagnostics
AER	=	Aerospazio Tecnologie
Ar	=	Argon
CRP	=	Cathode Reference Potential
DC	=	Direct Current
EGSE	=	Electric Ground Support Equipment
ESA	=	European Space Agency
FGSE	=	Fluidic Ground Support Equipment
FP	=	Faraday Probe
FU	=	Filter Unit
GFS	=	Gas Feeding System
HET	=	Hall Effect Thruster
IC	=	Internal Channel
IOM	=	Leibniz Institute of Surface Engineering
IEDF	=	Ions Energy Distribution Function
Isp	=	Specific Impulse
Kr	=	Krypton
MFC	=	Mass Flow Controller
MFR	=	Mass Flow Rate
OC	=	Outer Channel
OP	=	Operating Point
PSD	=	Power Spectral Density
RMS	=	Root Mean Square
RPA	=	Retarding Potential Analyzer
TtoPR	=	Thrust to Power Ratio
TB	=	Thrust Balance
TPS	=	Test Power Supply
TRP	=	Technology Research Programme
Xe	=	Xenon

I. Motivation and Background

THE TANDEM project[1-2], started at the beginning of 2021 and supported by a technological research programme (TRP) of the European Space Agency, involves the development of a high-power thruster in the 20 kW class. Aerospazio Tecnologie S.r.l. (AER) and the University of Pisa (UNI-Pi) joined their forces to design and build a Hall thruster, with its associated hollow cathode, capable of flexibly delivering powers going from 3 kW to a maximum of 25 kW. The manufactured unit represents one of the most powerful thrusters ever built and operated in Europe, and the unique European model with a dual channel configuration. The anodic block features two coaxial channels with magnetic shielding configuration designed with the scope to limit the channels' erosion rate, increasing thruster lifetime. The first prototypes (anodic block and cathode) were released in 2023 and, after initial checks at component level, were coupled for the first time in 2024. The performances of the whole thruster unit were characterized in the full power range using Xenon as propellant and in a reduced power range (up to 15 kW) using Krypton[3].

In early 2025, in the context of the CHEOPS-VHP-BB project (Consortium for Hall Effect Orbital Propulsive System - Very High Power - Building Blocks), an upgraded version of the hollow cathode was built and subjected to initial testing for flight-model qualification. The new cathode performed characterisation, environmental, and endurance tests. In parallel, an additional specimen was built in order to replace the early-developed cathode mounted on the TANDEM thruster. The new coupling test campaign was carried out at AER and aimed to demonstrate the thruster performances with alternative propellants. The thruster unit was characterized in a power range between 4.5 and 20 kW, activating the two channels both in single and dual mode, with discharge voltages of 300 V and 400 V. The TANDEM was operated with Xenon, Krypton, and Argon propellants.

The present paper reports the propulsive performances achieved, with particular emphasis on the discharge oscillation regimes observed and thermal aspects. Moreover, one of the aims of the CHEOPS-VHP-BB project was to adapt and validate the AEPD diagnostics system developed by the Leibniz Institute of Surface Engineering (IOM), one of the partners in the project. Therefore, the IOM system was integrated in the AER facility and used to characterize the plume exhausted by the thruster in terms of ion current densities and energies, instead of the

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standard AER diagnostic system already employed during the previous campaign[3]. The results of this characterisation are presented in this paper.

Another relevant aspect treated in this work concerns the vacuum chamber pumping capability. The importance of maintaining adequate background pressures represents a big challenge during the testing of electric propulsion engines, in particular for high-power thrusters when light gases are used as propellant (e.g., Argon). In fact, such a gas has a lower cryo-condensation temperature compared to typical propellant gases like Xenon. This paper describes the pump arrangements used in the test campaign.Last, this paper will discuss further developments of the TANDEM program, and in particular, of how to enlarge the thruster stability domain.

II. Experimental Apparatus

A. TANDEM Thruster

The unit tested in this work, hereunder referred to as "TANDEM", is a Hall Thruster composed of two coaxial channels and a centrally mounted cathode. The internal and external channels of the TANDEM are designed for a power ranging respectively from 3 to 7 kW and from 10 to 18 kW. The TANDEM thruster can work using one channel at a time or both channels simultaneously, featuring a nominal power of 20 kW and a maximum of 25 kW. The first unit released in 2023 (Figure II.1) is an elegant breadboard with an overall envelope (including mounting flange) of 37 cm in diameter, 17 cm in depth, and a mass lower than 60 Kg. A copper structure was added to the back of the thruster to allow reduction of the maximum temperatures in critical areas.



Figure II.1 TANDEM Thruster Breadboard Unit.

Each channel has an anode electrode, serving as a gas distributor, integrated within the boron nitride dielectric walls forming the discharge chamber. In the framework of the program "CHEOPS-VHP-BB", two monolithic anode distributors for both channels of the TANDEM thruster have been designed and produced by additive manufacturing employing the laser powder bed fusion technique. This solution allowed for a cost saving of about 60 % with respect to the traditionally manufactured items with similar internal geometry. A flow uniformity test, performed using customized equipment, was carried out to assess the flow distribution capability of the anodes, confirming the effectiveness of the employed manufacturing technique.

TANDEM magnetic circuit features a magnetically shielded topology and a magnetic pole shared by the two channels. In each one, two solenoids are used for main magnetization, whereas a trim coil is used for fine adjustment. The compliance of the thruster magnetic field with the simulations, in all its operative modes, has been demonstrated with a magnetic mapping campaign[4]. The tests were conducted using a customized Gauss-meter mounted on a commercial high-precision 3D printer. The values of the magnetic field components near the exit of each channel were measured for coil currents varying from -50% to +50% of design values. Experimental results show how the peak values of the radial components of the magnetic field are placed out of the channel, as

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expected for a magnetic shielding topology. The magnetic field characterisation was performed before and after each test campaign to confirm that no deterioration of the magnet circuit occurred after exposure to high temperatures.

B. Hollow Cathode

The TANDEM anodic block was coupled with a hollow cathode centrally mounted. This cathode is an evolution of the early unit (T2) built in 2023 and initially installed in the TANDEM thruster. The new cathode, Figure II.2, has been developed in the framework of CHEOPS-VHP-BB program. The purpose was to design, build, and test an engineering model (EM) of the cathode with a more robust configuration to withstand environmental tests and be able to work with a wide range of propellants[5].

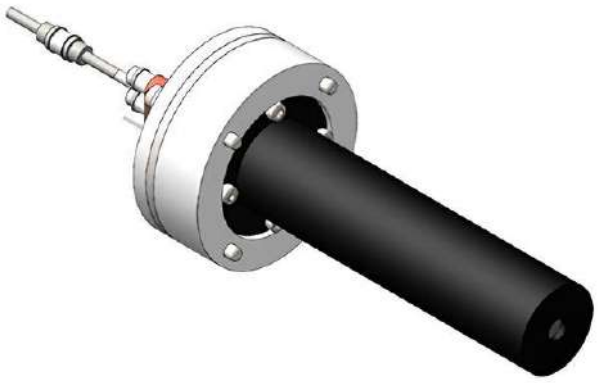


Figure II.2 CAD Drawing of the CHEOPS Cathode.

The CHEOPS cathode was built in multiple specimens. A first unit was subjected to initial testing for flight qualification, carrying out characterisation and environmental tests (mechanical and thermo-vacuum)[6]. The unit will then subjected to an endurance test. A second unit has been developed to be coupled with the PPS®20k thruster manufactured by Safran, which is one of the partners in the CHEOPS-VHP-BB consortium; results are presented in another paper of this Conference[7]. A third unit, hereunder referred to as "CHEOPS-C3", has been coupled with the TANDEM thruster.

The cathode is based on Lanthanum Hexaboride (LaB_6) emitter technology. The insert, shaped as a cylinder, located inside a refractory metal tube, surrounded by a heater. An additional electrode, the keeper, used during the ignition phase, contains and protects the internal elements from ion bombardment damage. The CHEOPS cathode has an overall length of 14 cm (up to mounting flange) and a mass of 600 g.

The activation of the cathode is performed by heating the emitter with a DC current source (up to 250 W) until it reaches the critical temperature for thermionic emission, and then by applying voltage to the keeper to initiate the discharge between the emitter and the keeper itself. The ignition voltage can be applied through a 60 V DC voltage source or, alternatively, using a train of high voltage pulses to enhance the process. The CHEOPS cathode can operate employing different gases as propellants. Tests performed using Xenon, Krypton, and Argon demonstrated the capability to flexibly provide discharge currents from 10 A to 100 A.

C. Thruster Test Arrangement

A commercial power supply sustains the plasma discharge in each channel of the TANDEM thruster. The internal anode was supplied by a 600V-25A DC programmable power supply. The external anode was supplied using an auto-ranging programmable DC power supply 800V-150A. Anode filter units are connected between the power supplies and anodes to damp the HET characteristic breathing mode oscillations. The discharge filter consists of an inductor in series to the anode line, with a resistor in parallel to dissipate the AC components. A capacitor is placed between the anode and cathode. Each discharge circuit branch, composed of a filter unit, harnesses, and feedthrough, nominally designed for a 5 kW thruster, has been proven to work up to 7 kW with maximum voltage up to 600 V and maximum current of 23 A. Multiple branches are connected in parallel to supply the external anode. Voltage measurements were performed both at power supply side and at thruster level, just upstream of the thrust balance input board. Electrical measurements were also performed using fast probes and an oscilloscope. A sketch of the electrical schematics arranged for the TANDEM thruster is depicted in Figure II.4. Additional commercial power supplies are used for magnetic coils and the cathode's heater/keeper (not shown in the given schematics).

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All power sources are hosted in a laboratory breadboard rack named “Test Power Supply 05” (hereinafter referred to as “TPS or EGSE”) designed and developed by AER (Figure II.3). The TPS also provides control for the flow units, data channels for upcoming test purposes and digital input/output lines to perform automatic control of the system. Research-grade propellants were provided to the TANDEM thruster using a customized Gas Feeding System (GFS) connected respectively to Xenon, Krypton, and Argon tanks. A gas pressure regulator was used to adjust the pressure at the inlet of GFS. The flow rate settings and measurements were performed using three commercial thermal mass flow controllers. One MFC was used for the cathode. Two MFCs were used, respectively, for the thruster inner and outer channels. The flows are set and read digitally with ±1% accuracy. The propellant lines pressures, upstream and downstream the mass flow controllers, were measured by means of electronic absolute pressure transducers.



Figure II.3 Test Power Supply (Main and Slave Units).

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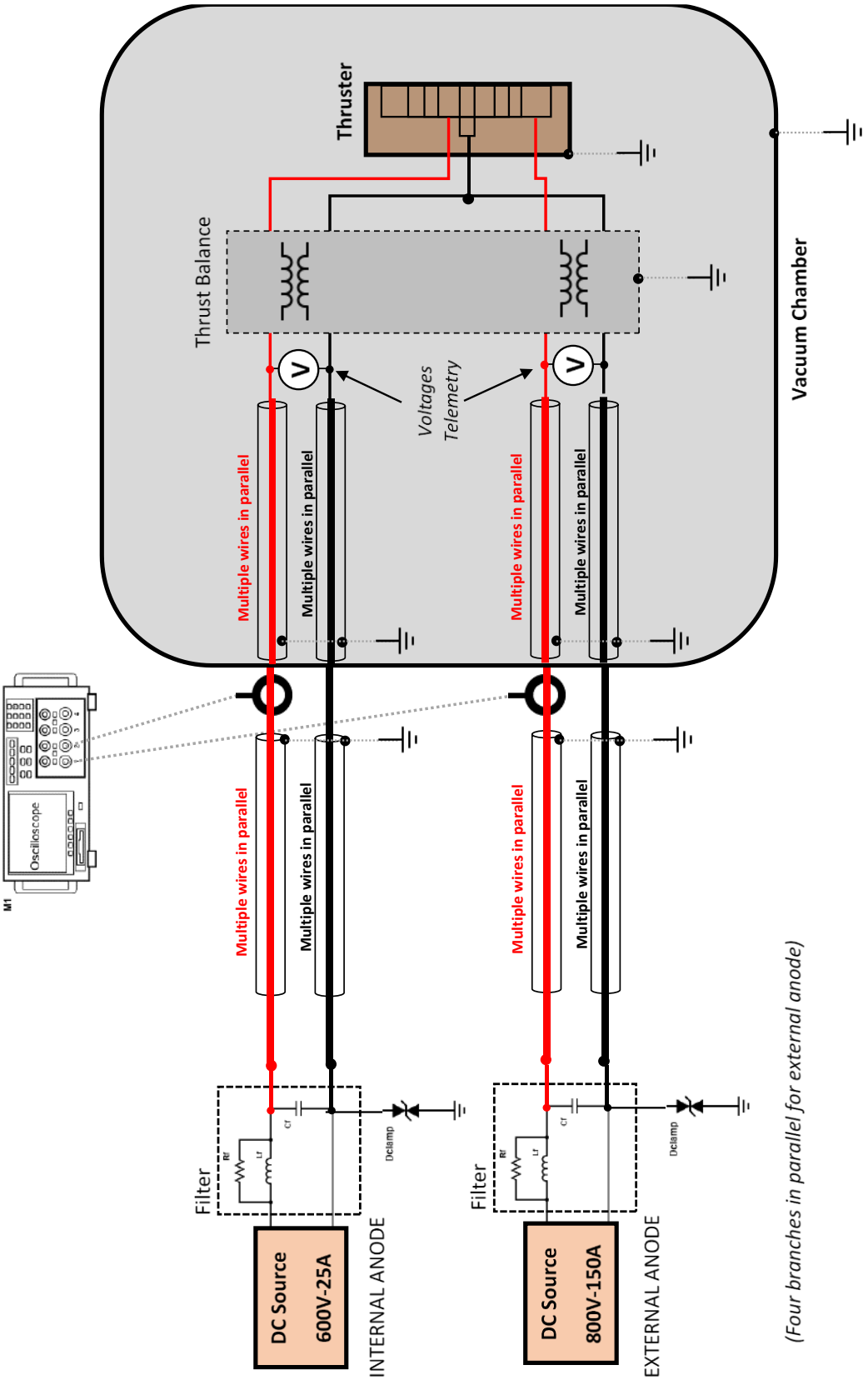


Figure II.4 TANDEM thruster electrical configuration.

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D. The Vacuum Chamber

The test campaign was performed at AER's main labs, located in Rapolano Terme (SI), Italy, in the LVTF-3 test facility, already used in the past for TANDEM testing. The vacuum chamber is 12.5 m long and has a diameter of 3.8 m for a total volume of about 140 m^3 (Figure II.5). This facility is conceptually similar to the other two large facilities available at Aerospazio (LVTF-1 and LVTF-2)[8], where extensive testing has been carried out in the last two decades on many different types of EP technologies employing both Gridded and Hall thrusters.



Figure II.5 LVTF-3 Vacuum Chamber.

Vacuum levels were measured by two ionization gauges (accuracy ±15%) calibrated for Nitrogen. For operations with other gases, a correction factor (the one provided by the gauge's manufacturer) was used. The gauges are regularly compared in-house on a dedicated facility with reference gauges calibrated according to standards so as to assess the accuracy over the time. The gauges are mounted on the chamber walls. The first one was positioned 3 m behind the thruster, pointed along its firing axis; the second gauge was mounted on the thruster exit plane perpendicularly to the thruster firing axis. The background pressure, used as a reference, was achieved by averaging the two gauges. A mass spectrometer is available to perform residual gas analysis.

The LVTF-3 has a data acquisition and control system architecture based on the National Instruments bus. Redundant systems allow minimizing risks and resting time in case of any failure. The computer system, hosting both DAQ and facility control, manages all pumping stages and records pressures and alarms. Specific software allows automatic operations. A high-power UPS supplies the test equipment in the event of an electric power loss, allowing continuous operations of the pumping system and test article under full power loss conditions. An additional electric diesel generator is available to allow pumping operation over long power interruption periods.

The LVTF-3 pumping architecture consists of four pumping stages, including mechanical, turbo-molecular, and cryogenic pumps. The full pumping speed was achieved using multiple cold heads surrounded by liquid nitrogen shrouds. In addition, a cryo-pump was used to pump light gases like hydrogen. The final set-up of the cryosystem was arranged to maintain an adequate background pressure during high-power thruster operations, with all the selected propellant gases. In this regard, Argon requires lower cryo-condensation temperatures compared with that typical of Xenon propellant. For example, in the range of 10^{-6} mbar, for a given saturation vapour pressure, Ar requires to achieve about 20-25 K lower cryo-condensing temperature respect to Xe. Therefore, in order to allow sufficient pumping performance for Ar, the cryopanels were shielded from the environmental thermal radiation in order to reduce the thermal loads and decrease the temperatures of the cryopanels. However, the shielding decrease also the particle transparency of the cryosystem, so as the pumping speed.

Figure II.6 gives the LVTF-3 pumping performances characterized with cold gas flows (top) and in hot conditions at the end of each firing cycle (bottom). The maximum values of the pumping speed achieved during this test campaign were 220 kl/s for Xenon, 300 kl/s for Krypton, and 400 kl/s for Argon. During firing with the thruster at maximum power, a minimal deterioration of the pumping capabilities (less than 10%) was observed. The upgraded cryosystem allowed keeping the facility background pressure below 4×10^{-5} mbar (Gas equivalent) during all testing, with a very limited pressure drift for firings of more than 1 hour.

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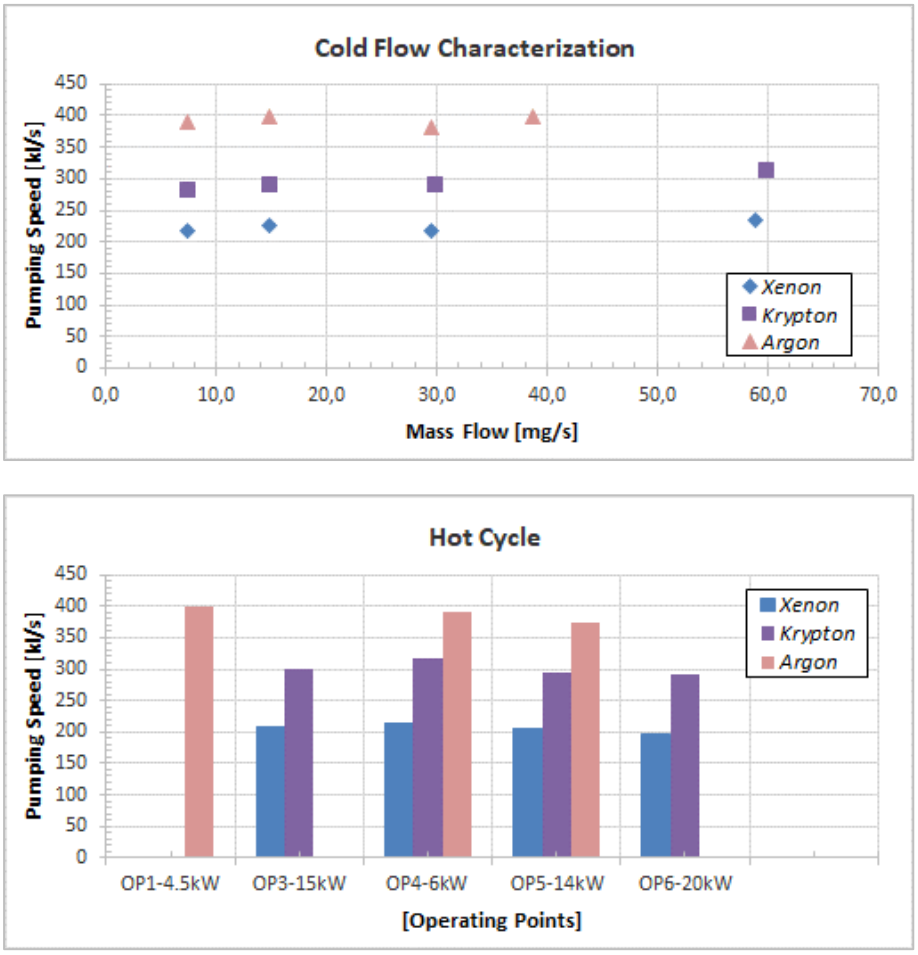


Figure II.6 LVTF-3 Pumping Performances.

E. The Thrust Balance

A single-axis thrust balance is used at Aerospazio facilities for direct thrust measurement (Figure II.7). The thrust balance consists of a parallelogram composed of two plates (upper and lower) connected by means of four bars and the corresponding hinges, so the thrust balance features a spring of a characteristic value. The stiffness of the hinges can be chosen so that thrusters of different weights and thrust levels can be accommodated on the upper plate (movable part). The lower plate is the fixed part connected to the test facility (inverted pendulum type). In order to damp oscillations, an eddy current brake is used. A water-cooled enclosure provides a thermally controlled environment for all vacuum sensors and electronic equipment. In order to provide better accuracy, the balance works on the principle of the null reading. This means that a sensor performs a continuous monitoring of the balance displacement with respect to an equilibrium configuration and provides the produced signal to an actuator, which counteracts the propulsive force of the thruster in order to maintain a zero reading (i.e., zero displacement) of the sensor. The actuation system is managed by a PID controller, which reads the displacement signals and drives the actuator. An additional mechanical system allows calibrating the balance, making it possible to tune the measurement correction factor.

The balance can be adapted to a quite large range of measurements. As for instance, in the campaign described in this paper, the balance was tuned for 2900 mN max thrust. The best accuracy is ever obtained by performing the thrust measurement just after a thruster switch-off. In fact, due to thermal drift, measurement uncertainties can increase over long firing periods. The balance calibrations are performed just before and after the switching-off of the thruster. However, the accuracy depends on several aspects (as the type of harness required for thruster supply, as well as the size and type of tubes employed for propellant distribution or thermal conditioning), therefore a specific analysis is performed for each concerned test. For this test campaign, the thrust accuracy was better than ±2 % of the reading over a single measurement performed upon calibration.

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Figure II.7 TANDEM thruster installed on the thrust balance.

F. The Test Set-up

A sketch of the set-up arranged inside the vacuum chamber is given in Figure II.8. The thruster was mounted on the thrust balance placed along the main axis of the vacuum chamber in a given axial station so as to have the exit plane of the thruster coplanar with the rotation axis of the diagnostic boom (a bow provided by IOM). In order to allow the integration between the thrust balance and the IOM's bow, the nominal thruster station was moved forward (toward the chevron target) about 50 cm. In this configuration, the distance from the thruster front face to the nearest tip of the chevron beam target was about 7.5 m.

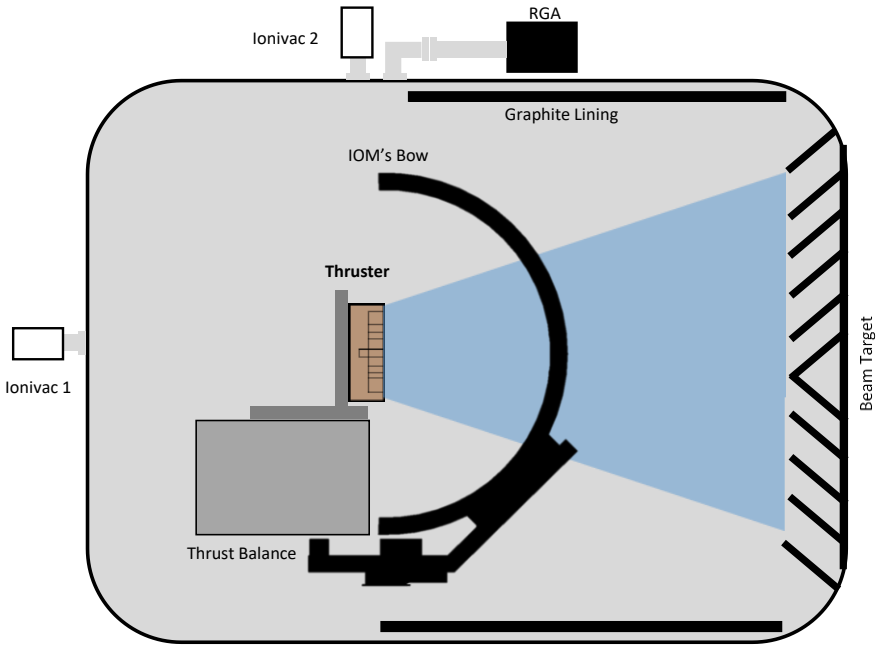


Figure II.8 TANDEM test set-up in LVTF3 vacuum chamber (Side View).

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The thruster test stand is equipped with a regulation mechanism allowing the positioning and orientation of the thruster in the chamber so that the thruster's vertical axis at the exit section corresponds to the rotation axis of the probe arm. Moreover, the center of the thruster circular exit section was aligned with the center of the semicircular rotating arm.

The semicircular diagnostic bow provided by IOM (Figure II.9) holds in total of 37 single Faraday probes and one RPA. The system is driven by a computer-controlled stepper motor that can rotate around the thruster with a maximum travelling range of ±95 deg. The Faraday probes were placed on the bow in steps of 5 deg. Each probe is mounted on the boom such that the collector faces the center of the thruster exit section, which is located at a distance of about 1 m. At maximum, 15 probes can be operated simultaneously for each scan. The probes selected can be fixed depending on the thruster characterisation needs. The selection can be easily changed from outside the vacuum chamber using a resistor and a selection board. The Faraday probes were used to measure the semispherical ion density distribution of the thruster plume. The RPA was mounted in the central position of the diagnostic bow, next to the central Faraday. Measurements were performed at selected bow's angular positions. The RPA was used to measure the ions energies. The results collected using Faraday/RPA probes are provided in this paper.

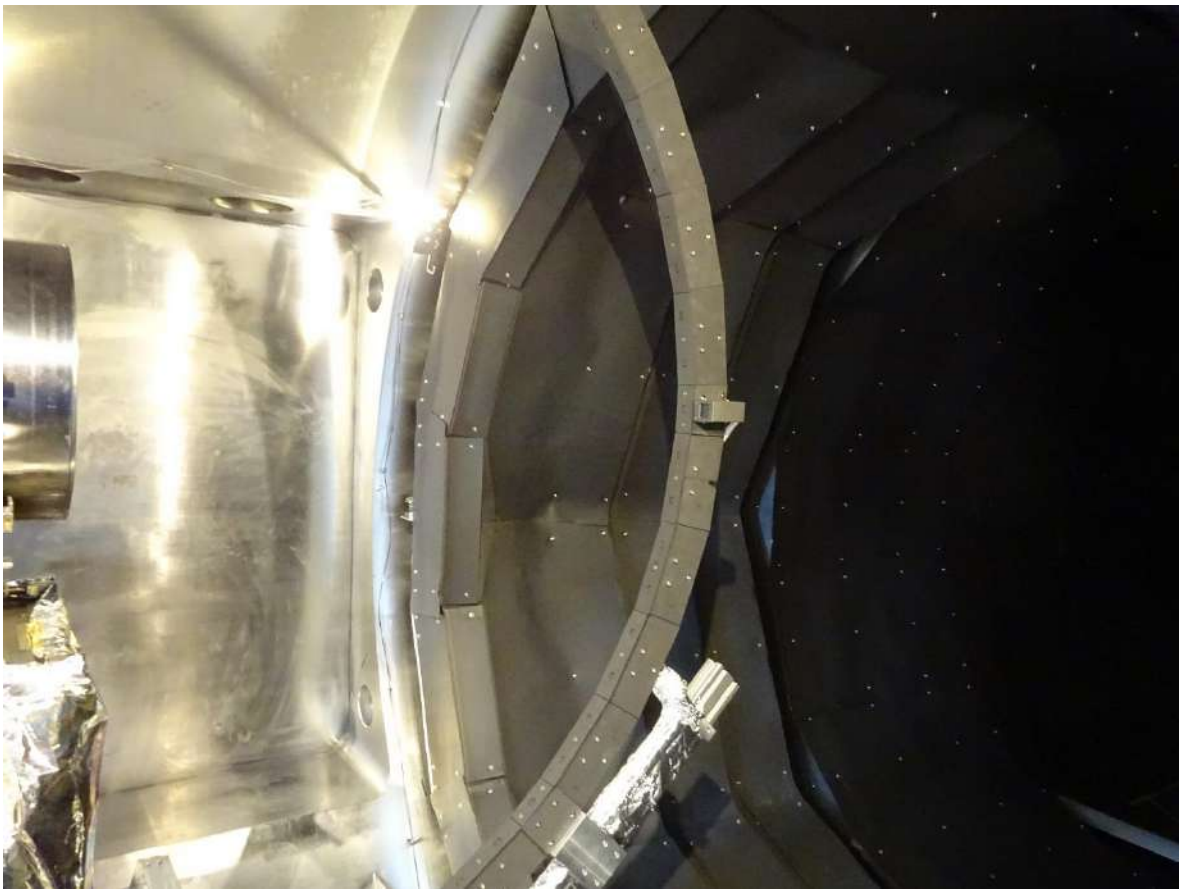


Figure II.9 IOM's bow in front of TANDEM thruster

A spot finder infrared camera was used as a thermal measurement diagnostic, in addition to thermocouples installed on the thruster and acquired by the TPS. It was installed inside the chamber on the horizontal thruster plane, at about 60 deg with respect to thruster axis and about 2 m far from thruster centre (Figure II.10). Thermal measurements were used to map the temperatures evolution of the critical parts of the TANDEM thruster, in particular on the anodes and on the ceramics of the channels. A commercial HD camera was available for a general view of the thruster. It was located outside the vacuum chamber, pointing to the thruster envelope through a borosilicate window.

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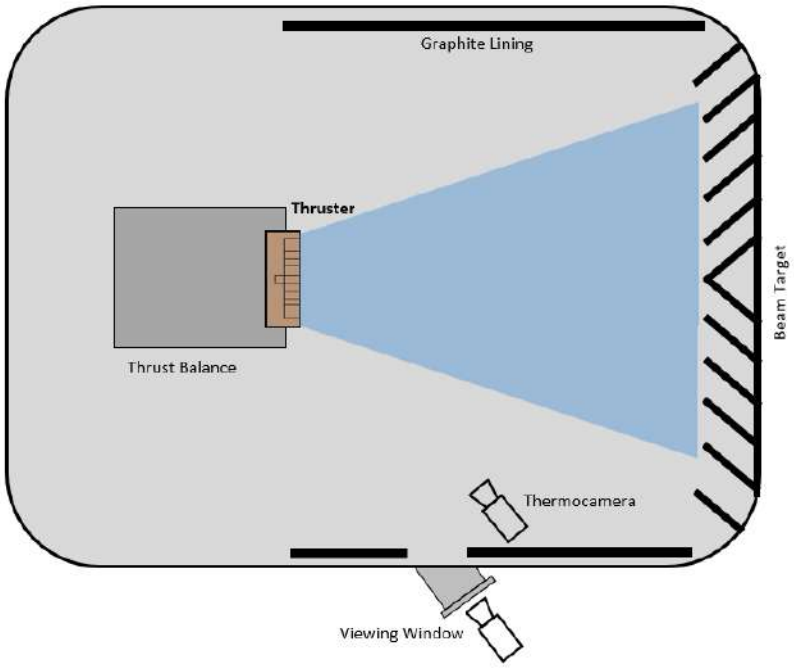


Figure II.10 Thermocamera set-up in LVTF3 vacuum chamber (Top View).

III. Test Results

The test campaign was aimed at characterizing the reference performances and the thermal behaviour of the TANDEM thruster with three different propellants (Xenon, Krypton, and Argon). The tests were carried out at four operating points, spanning the power range from 4.5 to 20 kW. Discharge voltages were changed from 300 to 400 V. First, the vacuum chamber was pumped down to reach the final vacuum. After cold outgassing and technological operations (gas flushing, vacuum characterisations), the thruster was fired at reduced power in dual channel mode (8 kW) to allow an efficient outgassing of the materials (in particular of anodes and ceramic channels) before starting performance mapping. After hot outgassing, the reference performance tests started. For each operating point, the following data were collected by direct telemetry:

- Electrical parameters (discharge current/voltage, coils currents/voltages…);
- Mass flow rates;
- Thrusts;
- Breathing mode frequencies;
- Temperatures and Pressures.

For each activation cycle, the thruster was fired for at least 30 minutes, in order to allow parameters stabilization, before starting plume characterisation. After plume mapping, at about 1 hour of continuous firing, the thruster was switched off to accurately assess the thrust, the efficiency, and the specific impulse in a quasi-steady state thermal regime. Mapping the thrust at the switch off allows minimizing the thrust balance thermal drift uncertainties so as to maximise measurement accuracy. The discharge current was managed using a closed control loop, which adjusts the anode mass flow rate to obtain the required current. The magnetic field was tuned in the last part of the stabilization time to improve the thruster stability, in particular to decrease the oscillations of the current. The propellant swapping happened without disconnecting any elements of the setup, but just switching between insulating valves.

The firing durations with Argon were reduced to 15 minutes for the stabilization and 30 minutes for the switch off, being Argon used for the first time with TANDEM thruster. In fact, data collection with this gas requires a more accurate assessment to understand the test article thermal behaviour before increasing firing times.

Figure III.1 shows the TANDEM thruster operated with different propellants in dual-channel mode. The following sections present and analyse the results obtained.

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Figure III.1 TANDEM Firing with different propellants (Xenon / Krypton / Argon).

A. Thruster Performances

Table III.1 lists the main parameters gathered in this test campaign using different propellants in four operating points (only three for Argon). The cells containing "na" in the table are referred to a channel not in operation at that time. The cathode mass flows were fixed for each gas and maintained constant during the overall test campaign. The cathode flows were selected in order to maintain cathode operations in spot mode in the overall range of extraction currents. An optimization of the cathode flows is foreseen in the future works after a clear identification of the thruster stability window. In order to decouple thruster performance from cathode one, before completing the cathode flow optimization, thruster anodic performances (full anodic block, including also magnets) are given between brackets. Figure III.2 (left) shows the main performances assessed for TANDEM thruster, fired with three propellants, plotted versus the total discharge current. For simplicity in data evaluation, in this work, 15 A are referred to as operations with internal channel only, 35 A with external channel only, and 50 A dual channel mode. Data collected with 300 V discharge voltage were plotted with empty marks. Data at 400 V were plotted with filled marks. The same figure, on the right, reports the comparison of the performances in the form of histograms for each operating point.

The results obtained show how the thruster was able to reach specific impulses greater than 2200 s in Xenon and more than 2300 s in Krypton. It is important to notice that TANDEM was fired only at 300-400 V in this test campaign. Greater specific impulses can be reached by increasing the discharge voltage above 500 V, as shown in previous test campaigns [3]. Total efficiencies achieved after 1 hour firing (quasi-steady state mode) were between 50-55% in Xenon. The transition between different operating regimes has been experienced. More precisely, the transition is referred to as the swap from a current oscillating regime characterized by an oscillation ratio below 10% to a regime in which the ratio rises above the 40-70%, with peak-to-peak current that can even reach 200-300% of the mean value. The current oscillations ratio is defined as the Root Mean Square (RMS) of the discharge current ripples normalized by the mean discharge current (DC component). The characteristics of these regimes and a discussion about the causes of transitions are analysed in the following section.

The maximum total efficiencies in Krypton, if operated with lower oscillations, were quite close to Xenon (max value 52%), whereas in Argon, efficiencies drop down to 30% or less. The operations with Argon experienced a severe level of current oscillations, producing a relevant heating in particularly on the anodes. For this reason, the operating power for performance characterisation in Argon was de-rated in the range going from 4.5 kW (internal channel only) to max 14 kW (external channel only). All the operating points tested in Argon showed an oscillatory behaviour.

In order to conclude this section, Figure III.3 reports the Thrust to Power Ratio plotted versus total Specific Impulse. The data collected at 500 V in Xenon during the previous test campaign are reported too. The thrust-to-power ratio in Xenon and Krypton ranges from 56 mN/kW at 1960 s to 43 mN/kW at 2420 s. The ratio drops in Argon, going to 30 mN/kW or below. One point in Krypton (41 mN/kW at 1800 s) experienced a high oscillatory behaviour, which worsens the final performances.

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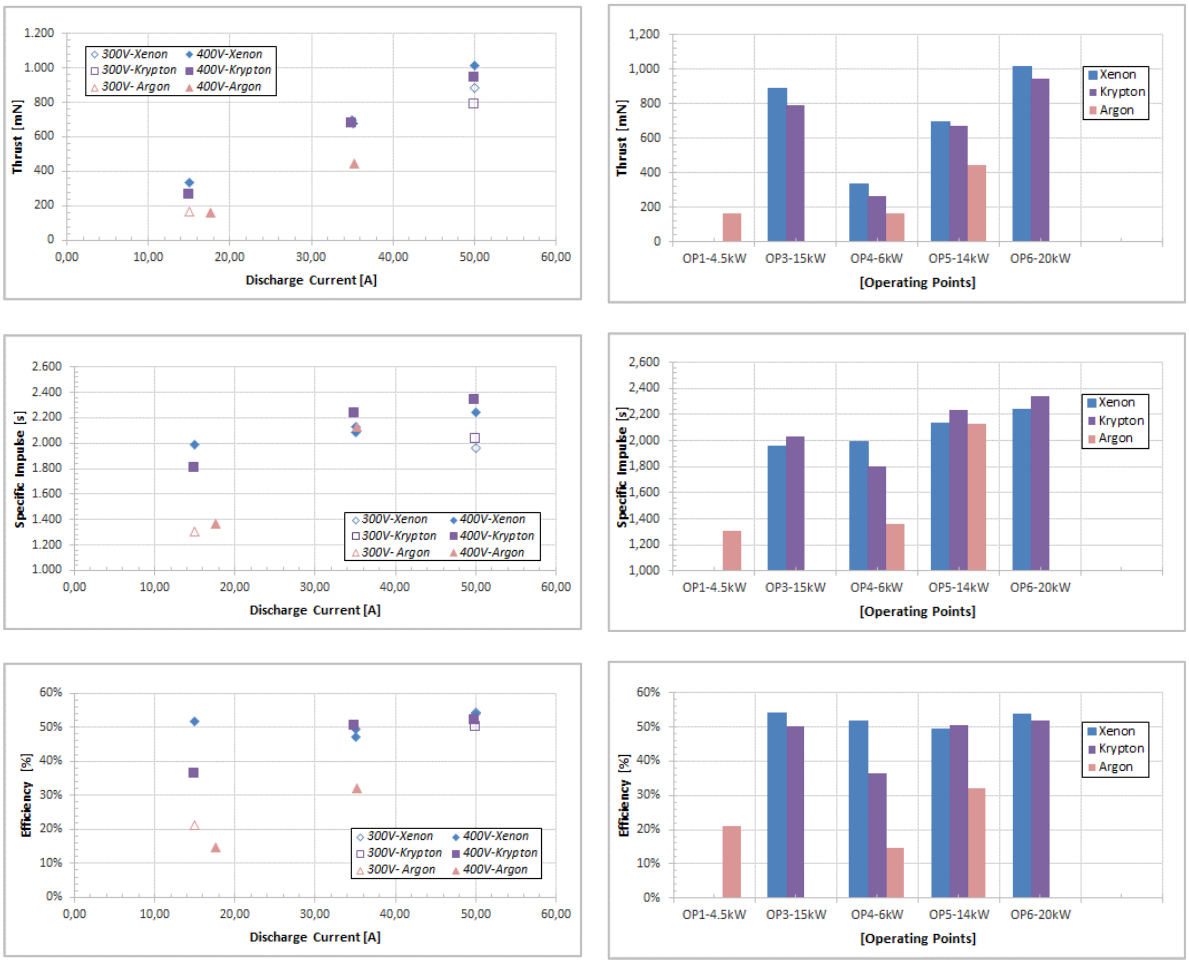


Figure III.2 TANDEM performances for different propellants.

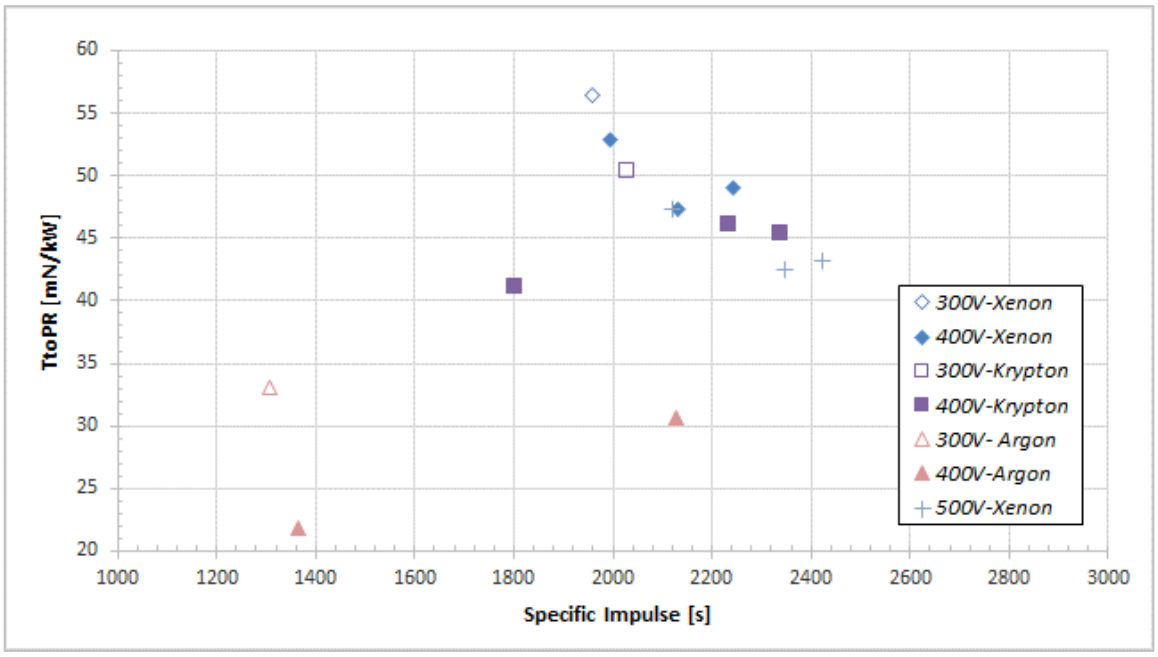


Figure III.3 TANDEM thrust to total power ratio vs specific impulse.

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Table III.1 TANDEM test results.

OP	Propellant	Vd IC [V]	Id IC [A]	Irms IC [%]	Vd OC [V]	Id OC [A]	Irms OC [%]	Id Tot [A]	V-CRP [V]	Mass cat [mg/s]	Mass Tot [mg/s]	Thrust [mN]	Isp * [s]	n * [%]	Pd tot [W]	Pcoils [W]	Ptot [W]	TP Ratio [mN/kW]	P avg [mBar]
OP3-15kW	Xenon	299.6	15.0	41.3%	299.6	35.0	20.9%	50.0	-5.5	3.0	46.1	887	1960 *(2096)*	54.2% *(58.0%)*	14988	728	15716	56.4	3.83E-05
OP4-6kW	Xenon	399.6	15.0	4.3%	na	na	na	15.0	-11.3	3.0	17.3	337	1993 *(2412)*	51.7% *(62.6%)*	5996	379	6375	52.9	1.39E-05
OP5-14kW	Xenon	na	na	na	399.6	35.0	41.8%	35.0	-5.2	3.0	33.2	694	2130 *(2342)*	49.4% *(54.3%)*	13993	677	14670	47.3	2.80E-05
OP6-20kW	Xenon	399.7	15.0	21.4%	399.6	35.0	51.2%	50.0	-5.6	3.0	46.0	1013	2244 *(2400)*	53.9% *(57.7%)*	19979	703	20682	49.0	4.02E-05
OP3-15kW	Krypton	299.5	15.0	73.1%	299.6	35.0	4.8%	50.1	-6.6	5.0	39.6	790	2032 *(2325)*	50.2% *(57.4%)*	14992	690	15683	50.4	3.58E-05
OP4-6kW	Krypton	399.6	15.0	73.5%	na	na	na	15.0	-4.6	5.0	15.0	266	1804 *(2703)*	36.3% *(54.5%)*	5996	478	6474	41.1	1.28E-05
OP5-14kW	Krypton	na	na	na	399.6	34.9	8.8%	34.9	-11.4	5.0	30.8	674	2234 *(2668)*	50.4% *(60.2%*	13961	681	14642	46.0	2.81E-05
OP6-20kW	Krypton	399.7	15.0	15.4%	399.6	35.0	42.4%	50.0	-6.4	5.0	41.1	944	2339 *(2662)*	52.0% *(59.2%)*	19965	864	20829	45.3	3.83E-05
OP1-4.5kW	Argon	299.6	15.0	75.8%	na	na	na	15.0	-5.5	6.5	12.8	165	1308 *(2651)*	21.2% *(43.0%)*	4489	494	4982	33.0	1.82E-05
OP4-6kW	Argon	398.9	17.6	155.0%	na	na	na	17.6	0.8	6.5	12.1	162	1363 *(2941)*	14.6% *(31.5%)*	7006	419	7425	21.8	1.76E-05
OP5-14kW	Argon	na	na	na	399.6	35.0	66.9%	35.2	-4.5	6.5	21.4	447	2127 *(3053)*	32.0% *(45.9%)*	13972	601	14572	30.7	3.24E-05

* Anodic block performances (including magnets) are reported between brackets

B. Discharge Oscillations Regimes

The thruster characterisation has also been obtained through the fast acquisition of electrical parameters. The frequency analysis of both internal and external channel currents has been carried out to assess information about oscillation regimes. The Power Spectral Density (PSD), defined as the logarithmic amplitude of the power spectrum of the discharge current, is plotted up to 1 MHz with a step resolution of 200 Hz. Two AC current claw clamps, placed respectively on internal and external anode wires downstream discharge filters, performed the fast measurements on the discharge currents. Figure III.4 presents the PSDs for each propellant used, with dashed lines for the internal channel and continuous lines for the external.

The operating regimes in Xenon were quite similar to what was observed in the previous test campaign for ESA-TANDEM programme [3]. Transitions between operating regimes were observed at both 300 and 400 V. They occurred mainly when the thruster was operated with external channel mode or in dual channel mode, in particular when the thruster exceeded given heating conditions. Thruster oscillations in Xenon show broad peaks spread in the area of the canonical breathing modes of Hall thrusters (10-30 kHz). The high oscillatory behaviour faced for Krypton and Argon (see discussion section below) is limited or does not exist with Xenon. Even the operations with Krypton were quite similar to those observed in the previous campaign. The increase of the magnetic field allowed to minimize oscillations of some operating points. In particular, the external channel at 400 V-35 A (OP5) in single channel mode (continuous red line) was fired with magnet current set to +40% with respect to nominal values, leading operations in optimal oscillation regime.

The thruster oscillations for Kr can be evaluated in Figure III.4 (Bottom Left). A Large part of the operating points tested showed an oscillatory behaviour with several harmonics up to 300 kHz. The discharge oscillations with Argon, in all tested operating points, showed harmonic oscillatory behaviours. Augmented magnetic fields, up to +50%, did not lower the oscillations' amplitude, allowing a transition to an optimal regime.

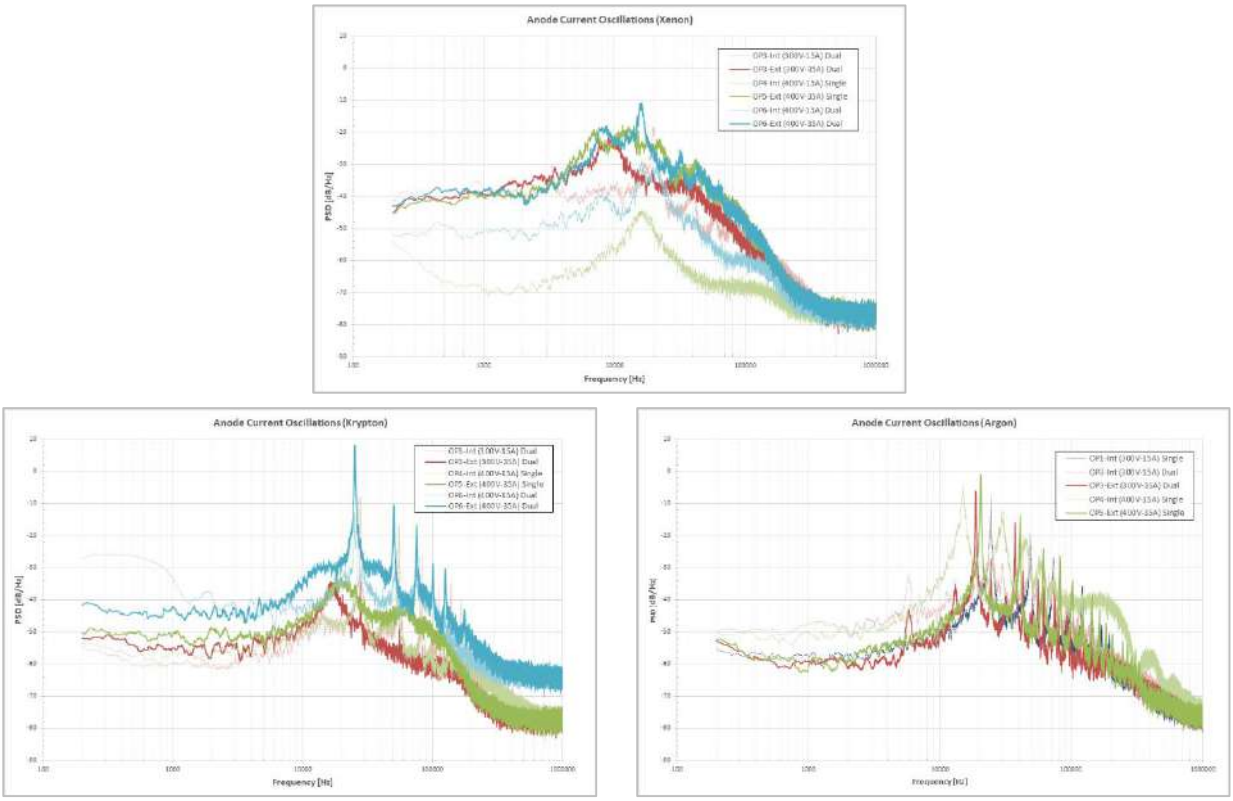


Figure III.4 TANDEM anode current oscillations in frequency domain.

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C. Thermal Analysis

The use of the infrared camera allowed for general thruster thermal mapping. It provided information about the temperature evolution in critical parts of the thruster, which can be useful during testing to understand the proper behaviour of the test article. Different areas of interest were selected to monitor temperatures over time (Figure III.5). The selected parts included the cathode exit surface, the areas covered by the two channels (both containing ceramic and anode), and four points placed on the anodes, two on the external and two on the internal.

All the data were gathered with emissivity ε set to 1 to simplify post-data elaboration. Whereas the data can be easily interpreted for a qualitative approach, real values need to be corrected using the spectral emissivity of the material in the viewed area. Indeed, it is known that a lack of precise knowledge regarding the real material emissivity can lead to significant uncertainties in temperature measurements. The estimation of possible uncertainties strongly depends on the characteristics of the observed materials. For example, in the cathode area, the emissivity can be considered close to one because only the external cathode surface is visible, and this part is made of graphite. In this case, the measurement uncertainty can be estimated to be less than 5%. Different considerations must be made for the discharge chambers, which are primarily manufactured using two materials: boron nitride for the ceramics and steel alloy for the anodes. The first material typically has an emissivity between 0.80 and 0.90, leading to an error of about ±10% in the measured value. On the other hand, the emissivity of the steel alloy has the largest range of variations and strongly depends on several aspects such as surface roughness and steel composition. For this reason, the difference between the real and calculated temperatures in the anodes can exceed 50%.

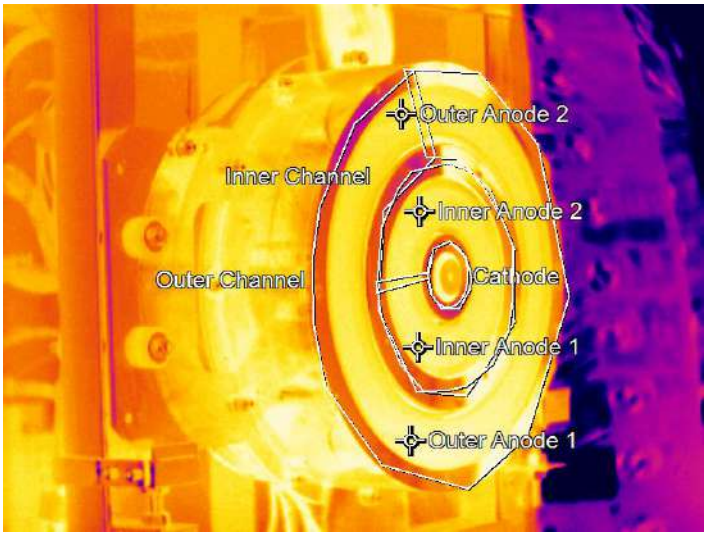


Figure III.5 TANDEM areas identified for thermal analysis.

Figure III.6 shows the thermal map of the TANDEM thruster operated at 20 kW in dual channel mode respectively using Xenon (top) and Krypton (middle). The temperature range palette is consistent across all images (150-600 °C). Images were captured every 20 minutes after the thruster was activated, and again, 20 minutes following its switch-off.

It can be observed that the temperatures achieved in Krypton are 10-15% greater, at the same operating point, compared to the temperatures attained in Xenon. The reported trends indicate that temperatures were quite stabilized after 1 hour of firing, but the thermal steady state of the thruster was not reached yet. A particular mention in the thermal analysis has to be done for the operating points performed in Argon. A significant increase in thruster temperatures was noted, especially on the outer ceramic and the anode (orange/dark blue lines in the plot). Variations in the curve slopes were linked to changes in the level of current oscillations. This confirms that temperatures in the discharge chamber are notably affected by the amplitude of current oscillations. To prevent potential damage, prior to a precise evaluation of the data, the testing power with Argon in this campaign, originally planned at 20 kW, was reduced. Moreover, the thruster was switched off after 30 minutes to prevent overheating of critical regions.

Figure III.6 (bottom) shows the temperature trend of Argon measured at the highest tested power (14 kW) using only the external channel. The thermal data achieved will be used to integrate the thermal models to assess the permissible TANDEM operating range in Argon.

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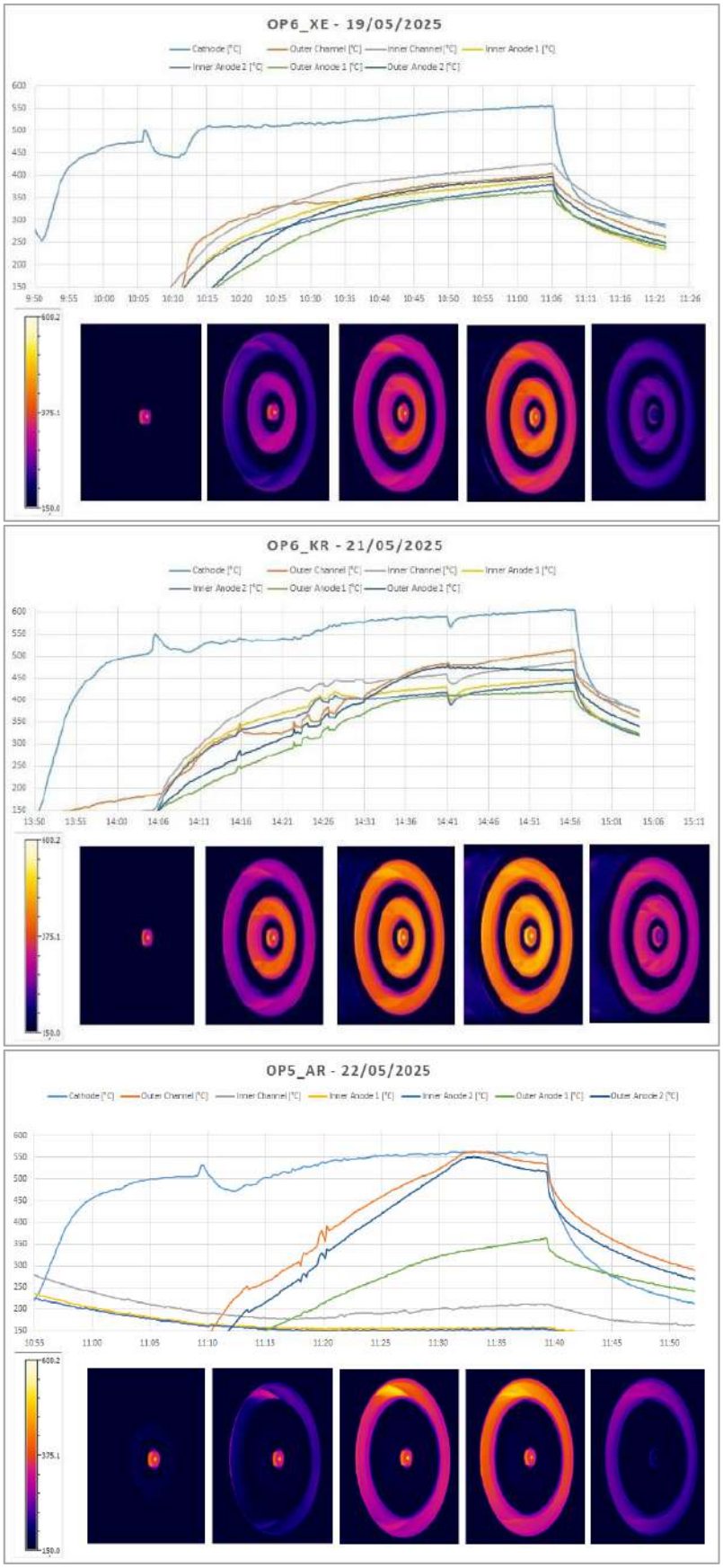


Figure III.6 TANDEM thermal maps (Xenon / Krypton / Argon).

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D. Beam Diagnostics Results (IOM)

The TANDEM plume behaviour was characterised in terms of ion current distribution and ion energy, using the diagnostic system provided by the Leibniz Institute of Surface Engineering (IOM). In fact, one of the tasks in the framework of the CHEOPS-VHP-BB requires adapting and validating the modular diagnostic system (AEPD) developed in previous research programmes[9-10], for utilization with high-power thrusters. For this reason, the beam diagnostic system present at Aerospazio and used in the previous test campaign with TANDEM[3], was placed in stand-by and replaced by the AEPD system in this work.

Figure III.7 shows the normalized ions current profiles acquired by Faraday equatorial probe (β=0 deg), plotted respectively with linear and logarithmic scale. Data presented are referred to TANDEM thruster operated at maximum power, 20 kW for Xenon and Krypton, 14 kW for Argon with 400 V discharge voltage. Data reported are the average of samples acquired in three consecutive scans. They show a good uniformity of the plume distribution in the equatorial plane at least for Xenon and Krypton. Ions current distribution in Argon results slightly shifted at negative α angle. The high oscillatory mode, specially observed in Argon, affected the ions current measurements, resulting in a significantly noisy signal. The peak intensity of the ion current, obtained in Argon at lower discharge current (35A against 50A), is significantly below the levels achieved with other gases, despite being influenced by high oscillatory modes that degrade the thruster's performance.

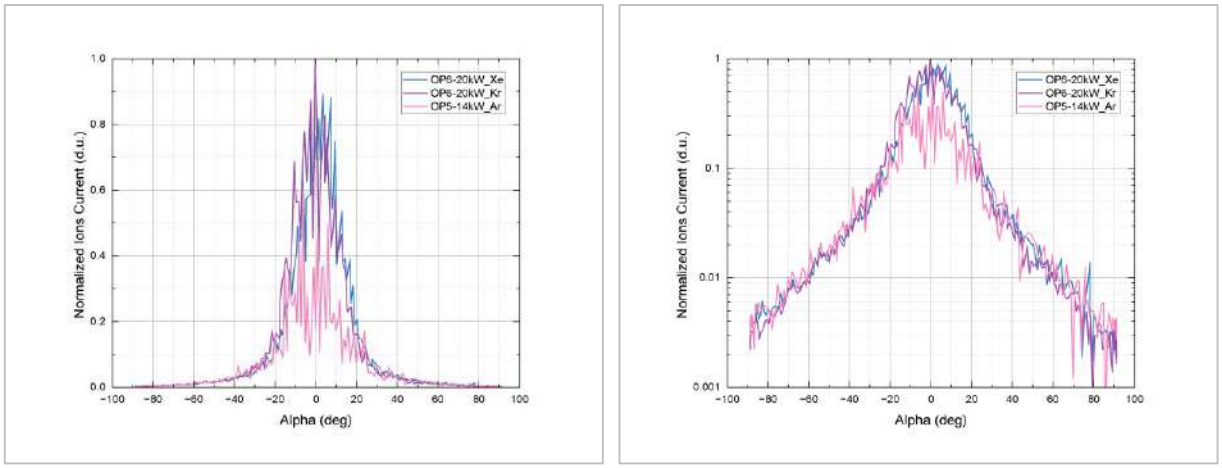


Figure III.7 Normalized plume equatorial ions current profiles (Linear/Log) for different propellants.

Figure III.8 shows the normalized Ions Energy Distribution Functions (IEDF) calculated in central measurement position (along the thruster geometrical axis) for the three gases at the operating points given above in this section. Energies (not corrected for CRP values) result to be highest for OP6 Xenon and lowest for OP5 Argon. Broadening appears to behave oppositely, being greatest for OP5 Argon and lowest for OP6 Xenon.

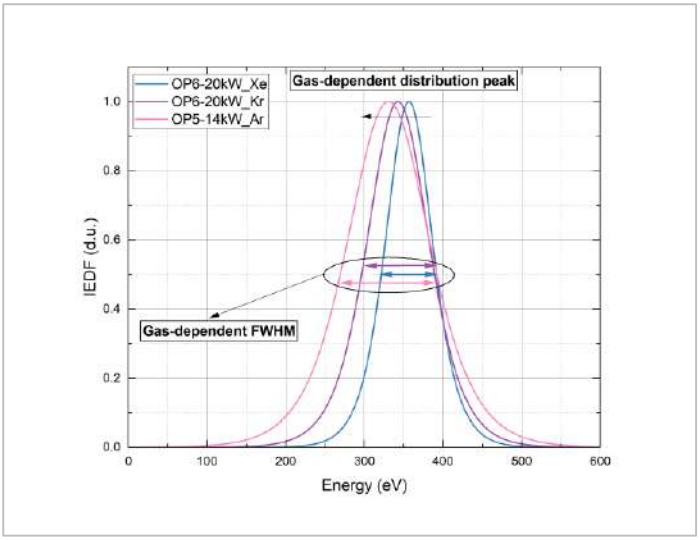


Figure III.8 Normalized IEDF (axial position) for different propellants.

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IV. Discussion

In this paragraph, we analyse and discuss on various literary works describing test campaigns carried out on similar thrusters. The results presented are compared with knowledge gained from the TANDEM experimental campaigns, aiming to clarify and understand certain behaviours observed and outline future development steps. Literature publications from the last ten years indicate that magnetic shielded thrusters can exhibit significant oscillations not seen in unshielded Hall thrusters. Richard R. Hofer and colleagues tested a 12.5 kW class magnetic shielded thruster HERMeS[11], observing significant oscillations during operation at voltages exceeding 500 V. M.J. Sekerak et al. [12], reported a study detailing how various oscillation types can coexist in magnetically shielded thrusters.

Three distinct oscillation patterns were detected with the TANDEM thruster. Two of them may be linked with the evidence of the typical breathing mode of Hall thrusters (MODE-1 and MODE-2), which is characterized by a peak spread around 10-30 kHz (Figure IV.1 / Cyan and Light Violet). In these modes, the RMS oscillations ratio may be under 15% of the average current (MODE-1 for the TANDEM thruster) or could increase up to 40-50% (MODE-2). The third regime noted exhibited a harmonic oscillatory mode featuring a distinct and narrow fundamental peak situated in the canonical breathing mode area, accompanied by numerous harmonics that extend up to 300 kHz (Figure IV.1 / Violet). In this mode, the RMS ratio can arrive up to 70% of the average current. This mode is associated to MODE-3 for TANDEM, and it was primarily observed with Krypton and Argon. Thruster performances and temperatures are closely linked to operating regimes, as demonstrated in previous test campaign performed at AER[3]. Operations in MODE-2 and MODE-3 exhibited lower performances. Thrust in MODE-2 was observed to decrease by over 10% compared to MODE-1 at the same OP, significantly affecting specific impulse and efficiency. Temperatures in MODE-2 and MODE-3 exceed those in MODE-1, resulting in poorer thruster performances.

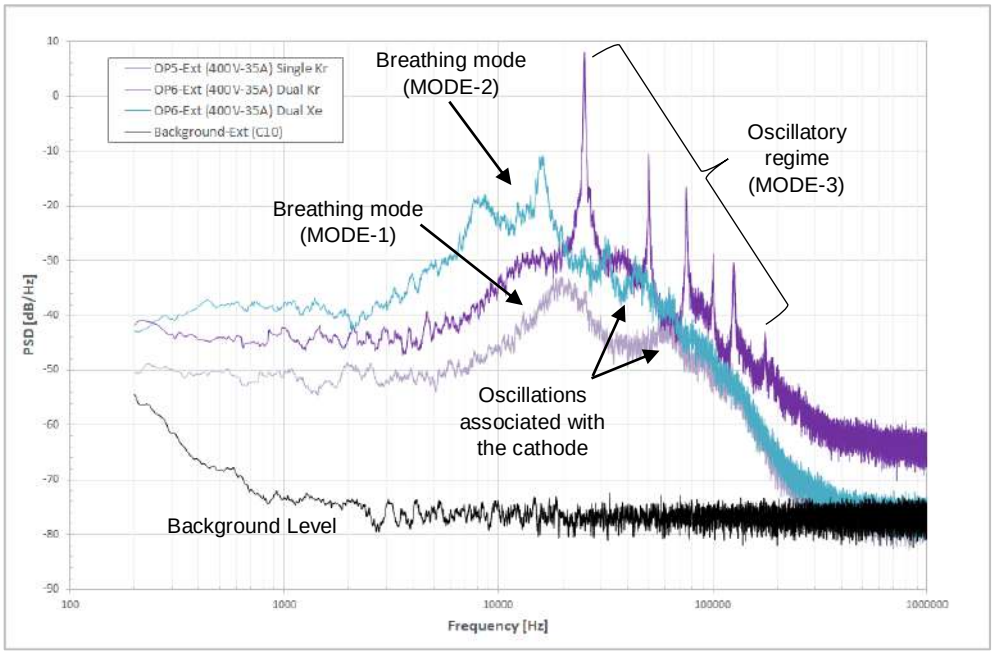


Figure IV.1 TANDEM characteristic oscillation regimes experienced.

The breathing mode oscillations at lower frequencies are not the only ones found in a magnetically shielded thruster. Based on the research carried out by Sekerak[12], a second mode is noticeable at higher frequencies reaching 100 kHz when the thruster operates in a quiet condition. It is associated to cathode oscillations. The Hall thruster, with magnetic shielding topology, appears to be more sensitive to those oscillations that are usually undetected in the unshielded model. The theory proposed in Ref. 12 suggests that magnetic shielded thrusters, pushing the ionization outside the discharge channel, are more sensitive to those oscillations. Another study, conducted by Shadrach T. Hepner[13], examines how cathode oscillations exist both with cathode centrally or externally mounted respect to the thruster. Oscillations in the 30-80 kHz range, detected with the TANDEM thruster, might be linked either to the cathode or to harmonics of the oscillatory breathing mode, which begins to emerge here and gains relevance at elevated discharge voltages (Figure IV.1 / cyan). Further investigations are required to determine if those oscillations are linked to the cathode, especially when the mass flow rate optimization will be conducted. Finally, as demonstrated by M.J. Sekerak in Ref. 12, azimuthal spoke oscillations may occur alongside breathing mode and cathode oscillations. It is still uncertain, for the TANDEM thruster, if spokes oscillations occur simultaneously with the oscillatory regimes and how, if at all, they influence the

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performances. Further studies employing the system created at AER[14], based on optical diagnostics and ultra-fast imaging, will be undertaken in upcoming projects to explore this aspect.

The appearance or disappearance of the aforementioned modes, significantly influencing the RMS and Peak-to-Peak oscillations, can be defined as a transition. Changes and shifts between modes, referred to as “modes hopping,” were detected with the TANDEM thruster starting roughly ten minutes after start-up at certain heating conditions, in particular when thruster was operated at discharge voltages higher than 350 V. The factors driving the changes in TANDEM oscillation regimes require additional examination and thorough comprehension. Alongside the physics studies and design enhancement, a method to determine the stability window of the TANDEM thruster and its margins must be explored. Recent studies[15-16], conducted by Benjamin A. Jorns, on the H9 Hall thruster developed by the Jet Propulsion Laboratory and University of Michigan, revealed the mechanisms behind mode transitions in magnetically shielded thrusters. Research indicates that the thruster stability domains relies on various design factors, including acceleration length, channel size, and the intensity of the magnetic field. Additionally, it relies on operational factors such as discharge voltage and current levels. Specifically, shielded thrusters exhibit a transition to instability when the discharge voltage increases at relatively low discharge currents. In recent work conducted by Richard R. Hofer on the H10 magnetic shielded thruster at NASA JPL[11], it is shown that the thruster can be operated at high voltages, within a low oscillation regime, increasing power density.

Even the temperature of the gas distributor plays a relevant role on the thruster’s stability, changing the ionization process and especially the neutral transient time[16]. R.A. Martinez[17] has experienced how different anode temperatures may affect the neutral residence time and velocity. This may clarify certain phenomena seen with the TANDEM thruster, which are, in our view, related to specific heating conditions of the gas distributor and the ceramic walls. The study, conducted by Benjamin A. Jorns[16], shows the effect of varying magnetic field strengths and discharge currents on the oscillations level. The complete transition to a stability region takes place only beyond a defined discharge current indicated as the "stability barrier”. This behaviour is in agreement with experiments carried out in this campaign on the TANDEM thruster, indicating that, at certain operating points, thruster works below the current density necessary for transition to take place. This can be more clearly understood by examining Figure IV.2 from Ref. 16. As shown in the figure, when the H9 thruster was operated below 10 A, changing the magnetic field affects only in part the oscillations amplitude. A clear transition to quiet oscillations state occurs only beyond a given discharge current (stability barrier). Anyway, the variation of magnetic field can shift the transition point to lower discharge current, thereby enlarging the stability window. Identify the discharge current domain stability in the TANDEM thruster will be part of future work.

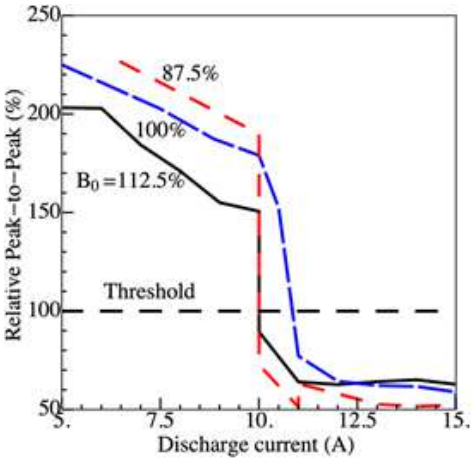


Figure IV.2 Response of H9 thruster stability by changing magnetic field[16].

V. Conclusion

A 20 kW class Hall Thruster (TANDEM) with two coaxial channels has been designed by the University of Pisa and manufactured/tested by Aerospazio Tecnologie S.r.l. The thruster, coupled with the new cathode developed in the framework of CHEOPS-VHP-BB project, has been subjected to a test campaign in order to characterize its performances with three different propellants (Xenon, Krypton, and Argon). The thruster was operated both activating only one channel at a time, and in the dual channels configuration, with a discharge power range going from 4.5 to 20 kW and discharge voltages of 300 and 400 V. The results obtained show how the thruster was able to reach specific impulses greater than 2200 s in Xenon and more than 2300 s in Krypton. It is important to notice that TANDEM fired only at 300-400 V in this test campaign. Greater specific impulses, up to 2400 s in Xenon, were reached at 500 V during the previous campaign. Efficiencies achieved after 1 hour firing (quasi-steady state mode) were between 50-55% in Xenon and up to 52% in Krypton. Operations with Argon were performed with a high level of current oscillations, producing a relevant heating, in particular on the anodes. Efficiencies in Argon drop to 30% or less.

Three different oscillation regimes were observed with TANDEM thruster. It was observed how working in different regimes and oscillatory modes affects the thruster performances and temperatures. Severe oscillating mode has been observed, especially with Krypton and Argon. Thruster oscillations in Xenon show broad peaks spread in the area of the canonical breathing modes of Hall thrusters. The highly oscillatory behaviour faced for

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Krypton and Argon is limited or does not appear with Xenon. Optical diagnostics and ultra-fast imaging are foreseen to be employed in additional future investigations to study the nature of oscillations.

Concerning the future developments of the TANDEM thruster, additional testing activities are foreseen in the frame of the TRP project granted by ESA. In parallel with the studies of physics and the upgrade of the design, further analysis needs to be conducted on the TANDEM thruster to better identify its stability windows, and, in particular, of how to enlarge the thruster stability domain at higher discharge voltages in order to maximize the specific impulses achievable. An optimization of the cathode flows is foreseen in future development works, which will follow the identification of the stability window of the thruster, together with the demonstration of the TANDEM thruster's full thermal stabilization.

The TANDEM project also represent an interesting test for new technology developments in terms of configurations, materials, thermal dissipation, and manufacturing processes, so as new advanced configurations, such as that developed by JPL in the H10 thruster, could be implemented in the near future in the TANDEM thruster. The availability of advanced optical diagnostics at Aerospazio (OES, LIF) and several Large Test Facilities with high pumping speed allow to perform extensive experimental investigations so as to facilitate the understanding of the physical phenomena currently limiting the performances of the European vs. US technology.

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