Development of a 10-30 kW Augmented Field MPD Thruster at SITAEL

IEPC-2019-872

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Alena Kitaeva [1], Tommaso Andreussi[2], Daniela Pedrini[3], Mariano Andrenucci[4]
SITAEL S.p.A., Via A. Gherardesca 5, 56121 Ospedaletto (Pisa), Italy

and

Giulia Becatti[5]
University of Pisa, Pisa, 56120

Abstract: The paper describes the early phase of development of a gas-fed, rail-type, Augmented Field Magnetoplasmadynamic Thruster, recently undertaken by SITAEL. The prototype relies on the HC60 hollow cathode to feed and ionize the propellant, and generate a steady electrical discharge. The produced plasma flow is then accelerated by the Lorentz force associated with the self-induced magnetic field augmented by an external magnetic field applied perpendicularly to the thrust vector. The target power range for this thruster class was set at 10-30 kW. This present work describes the results of a preliminary test campaign held at power levels below 4 kW with xenon and argon propellants. The results of this early phase support the feasibility of the concept and provide useful guidelines for further phases of thruster development.

I. Introduction

THE magnetoplasmadynamic (MPD) thrusters, also known as Lorentz-Force Accelerators (LFA), rely on the interaction between current and magnetic field to accelerate plasma. In the conventional axisymmetric self-field MPD thruster, the current flows between the coaxial cathode and anode, inducing a magnetic field in the azimuthal direction. The resulting Lorentz force is in the axial direction and directly accelerates the plasma. As this force scales as the square of the current, thrusters that rely on the self-induced magnetic field only (SF-MPD thrusters) are usually effective at very high discharge currents (kA) and high power levels (MW). In order to improve the MPD thrusters performance at lower power, configurations with an externally applied magnetic field (AF-MPD thrusters) were developed and extensively tested by many researchers [1].

For conventional applied-field axisymmetric configurations, the applied magnetic field is oriented along the thruster axis and generates a Lorentz force in the azimuthal direction, thus inducing a swirl motion in the plasma. Part of the rotational energy is then converted into axial kinetic energy through the conservation of the angular momentum. As the force associated with the applied magnetic field is not parallel to the thrust vector, the resulting acceleration process is more complex and its effectiveness is often limited.

Removing the constraint of axial-symmetry, it is possible to look at alternative thruster configurations in which the applied field directly adds to the self-induced magnetic field. An example of such configurations is a thruster with a

[1] Electric Propulsion Engineer, alena.kitaeva@sitael.com
[2] Technical Manager, tommaso.andreussi@sitael.com
[3] Electric Propulsion Engineer, daniela.pedrini@sitael.com
[4] Propulsion Division Head, mariano.andrenucci@sitael.com
[5] PhD Student, giulia.becatti@sitael.com

rectangular acceleration channel fitted with parallel electrodes on two sides. In this case, an external magnetic field can be applied in the direction transversal to the flow, orthogonal to both the electric field and the thrust direction. Only limited research activities on the cross-field thruster concept were performed in past years. A review of such activities is presented in Section II.

Benefitting from an extended heritage in the development of SF- and AF-MPD thrusters, SITAEL recently started a research project on cross-field configurations. The main objective of the project is to investigate, both from the theoretical and experimental viewpoints, the performance and operation envelope of these configurations. In particular, a dedicated test campaign on a low-power (10-30 kW) cross-field thruster prototype is currently underway. The tests described in this paper refer to a preliminary setup intended to test the basic physical interactions involved in the acceleration mechanism. The propellant, supplied through the HC60 hollow cathode into the discharge region, is accelerated by the Lorentz force proportional to the product between the discharge current flowing between the cathode and suitably placed anode and the transversal magnetic field. In the present paper, results obtained for different values of the operating parameters are described and analyzed.

II. Literature review

Main research activities on the cross-field MPD thruster concept were performed in Japan, in the period 2009- 2015. They were focusing on low power (0.4 – 2.5 kW) [2, 3] and medium power (28 -173 kW) [4] configurations. These activities demonstrated a general concept feasibility but low thrust efficiency (<16.5%). Table 1 presents the main operating parameters and test results of these works.

Table 1. Overview of the main activities available in literature.

Parameter	**Nagoya University, Japan, 2015 [4].**	**Tokyo University, Japan, 2010 [2].**	**Nagoya University, Japan, 2012 [3].**
Inlet	Through Hollow Cathode	Inter-electrode space	Through 1 HC/ Through 2 HC
Total mass flow rate, mg/s	0.41-2.1	200	1.2-2/4
Discharge current, A	5-15	130-300	8-10/10
Keeper current, A	2	-	2
Applied magnetic field strength, T	0.2-0.23	0-1.13	0.12-0.38
Magnetic field generator	NdFe permanent magnets	Coil	Coil
Power range, W	450-2850	67260	1000-2000/600
Thrust, mN	5-26	1000-3370	1.5-9/4
Inter-electrode distance, mm	5-15	10	20-40
Cathode position	Vertical	Horizontal	Vertical/Vertical+Horizontal
Cathode type	One HC	3 rod cathodes	One HC/2 HC
Propellant	Ar	Ar	Ar
Cooling system	Water-cooled anode	Radiative	N/A
Chamber pressure during operation, mbar	7.0×10^{-4}	2-7	2.8×10^{-4}
Thrust balance	Pendulum type	Target method	Pendulum type

In all these works, the thrust and voltage exhibited a linear rising trend with the increase of discharge current and magnetic flux density.

In Nagoya University [2, 3] authors investigated two configurations with hollow cathodes, which are similar to the one chosen for the present test set-up. In the first configuration, the hollow cathode was positioned vertically, facing the anode. The second configuration had two cathodes: one placed horizontally along the thruster axis and another one vertically. The authors investigated the thrust dependence on the product of the current, magnetic field strength and inter-electrode distance I_dBH and observed a linear tendency. The experimental curves they obtained were fitting well the theoretical values at the level below 4 mN. For higher values of I_dBH, the measured thrust was significantly lower than the theoretical value. The effect was explained through the non-ideal direction of the discharge current. Ideally, the discharge current should be perpendicular to the magnetic field lines. The low efficiency was attributed to the high electrode losses and a low plasma density in the channel. The implementation of the second cathode did not seem to improve the results significantly.

In Tokyo University a different electrodes configuration was investigated [4]. The thruster featured three rod-cathodes and three anodes of the same shape. The thruster was operated quasi-steadily and at higher power levels with respect to those from Ref.2 and Ref.3. The obtained efficiency was higher. However, the reported backflow pressure value is high and could have affected the test results. Trends observed are similar to those of Nagoya research group. Thrust and thrust efficiency were rising with both magnetic field and discharge current.

The results of these works indicate the feasibility of the concept and unleash several criticalities, like the cathode positioning and the achievement of the necessary plasma density in the discharge chamber. Moreover, for the proper concept operation, both electrons and ions should be magnetized. The estimated plasma parameters for effective operations with argon of augmented-field MPD thruster are presented in Table 2.

Table 2. Plasma parameters.

Parameter	Magnetic field strength, T	
	0.1	1
Electron and ion temperature, $T_{e,i}$, [eV]	3	
Plasma density, n, [m^{-3}]	10^{21}	
Chamber scale parameter, L, [m]	0.01	
Debye length λ_D	$4.07x10^{-7}$	
Ion Larmor radius, [m]	$1.576x10^{-2}$	$1.576x10^{-3}$
Electron Larmor radius, [m]	$5.841x10^{-5}$	$5.841x10^{-6}$
Ion Hall parameter	$1.484x10^{-2}$	$1.484x10^{-3}$
Electron Hall parameter	4.005	40.05

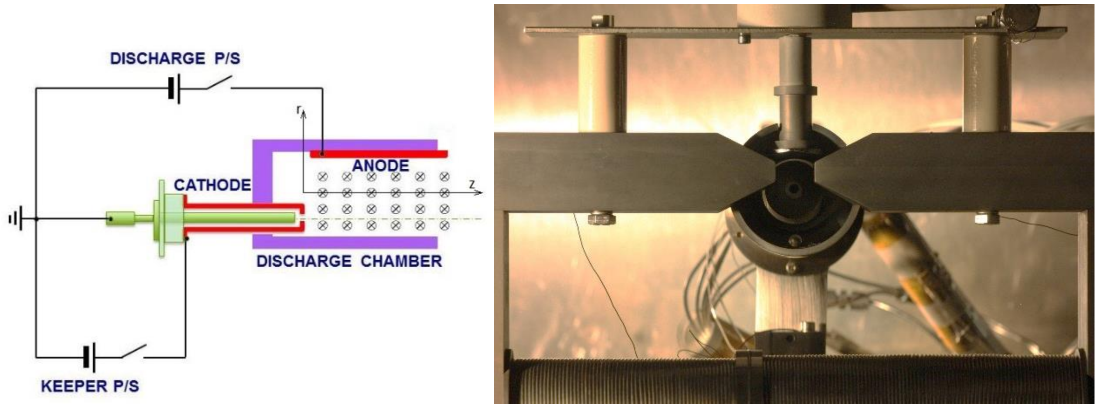
III. Experimental set-up

The test set-up, described in this work, was meant as an initial step for the development of the 10-30 kW Augmented Field MPD Thruster. At this stage, we tried to understand the main tendencies and evaluate further the design approach. A first set of the experiments was performed without the discharge chamber and with Xe propellant. Then we added the discharge chamber to the test set-up and tested it first with Xe and then with Ar.

A. Overview of the Augmented Field MPD Thruster test set-up design

The conceptual scheme of the test set-up is presented in Fig.1 a). The propellant is feed through SITAEL's HC60 hollow cathode, positioned axially. The thruster performance with two propellants, xenon and argon, was investigated.

The distance between the centers of the molybdenum disk anode and the cathode exit was 20 mm both along z and r axis (see Fig.1). The magnetic field was generated with an inductance coil connected to a ferromagentic circuit. The ferromagentci circuit poles were positioned in a way that the maximum magnetic field intensity would be along the central axis of the set-up (axis z), between the cathode axis and the anode surface, at the center of the anode. In order to vary the magnetic field strength, the current in the solenoid coil was regulated. The set-up allows to achieve a maximum of 0.325 T (according to the magnetic field simulation). Two test set-up configurations have been investigated: one without the discharge chamber and another one with the cylindrical ceramic channel acting as a discharge chamber. The set-up was radiatively cooled.



a) b)

Figure 1. a) Conceptual scheme of the Augmented Field MPD thruster, b) simplified test set-up.

The thruster ignition procedure was organized in the following way, first the cathode was ignited with keeper, and then the anode-cathode discharge was turned on with no magnetic field. The next step was to switch off the cathode keeper, allowing the thruster to maintain the discharge on its own. The measurement of the discharge voltage with no magnetic field were also a part of this experimental campaign. The last step was to turn on and increase the magnetic field strength and to vary the discharge current values according to the chosen operating conditions (See Table 3).

Table 3. Operating parameters.

Parameter	No channel, Xe	With channel, Xe	With channel, Ar
Discharge Current range, I_d, [A]	10	10-30	10-20
Magnetic Field Strength range, B, [T]	0-0.07	0-0.088	0-0.018
Mass Flow Rate, $\dot{m}$, [mg/s]	2-3	2-5	1-1.5

B. Overview of the test facility and equipment

The tests were performed in SITAEL's LFF vacuum facility. The facility consists of a main chamber and an auxiliary chamber. The main chamber is 2.8 m long and has an inner diameter of 1.2 m. The vacuuming of the main chamber was performed with one rotary pump (28 m^3/h), one turbomolecular pump (2000 l/s), one cryo pump and one custom cold head. The auxiliary chamber has a dedicated pumping system and is seperated from the main chamber with a large gate valve. There are two pressure sensors in each chamber, constantly monitoring the pressure level. The pumping system allowed to maintain the vacuum level during this test campaign below $4x10^{-5}$ mbar with Xe and below $4x10^{-4}$ mbar with Ar. The LFF test facility is presented in Fig.2. The vacuum facility is made of the non-magnetic stainless steel which allows to use the pendulum type thrust balance even with the strong magnetic field MPD thrusters without the problems of magnetic interaction of the test set-up with the chamber walls.

Figure 2. SITAEL LFF vacuum facility.

The thrust balance used in this test campaign was the SITAEL single axis thrust balance developed for the 20 kW Hall Thruster programme. The thrust stand features a double pendulum configuration and can sustain the weight of the test set-up. The working principle of the stand is based on the measurement of the strain on the flexual balance elements with high precision load cells. The leveling of the thrust stand is performed during calibration though a tilting platform mechanism.

Due to the current test set-up limitations, in this test campaign we measured only the trust increment (ΔT) corresponding to the application of the magnetic field, but not the absolute value of thrust. The accuracy of the measurements was estimated to be about ±0.5 mT.

IV. Test results and Discussion

A. The effect of the main experimental parameters on the performance with Xe

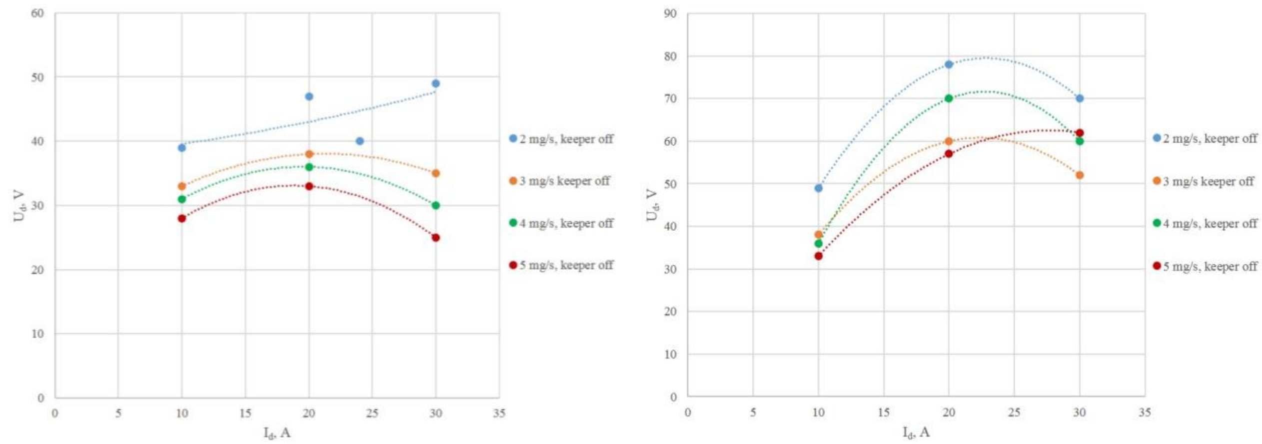
The results of the test campaign with Xe indicated the discharge voltage increase with the strength of the magnetic field and no significant dependence of the thrust increment on the mass flow rate. In this preliminary stage of the thruster development, the set-up was tested only up to 3.5 kW – 4 kW due to the test set-up limitations. The main test results are summarized in the next two sub-sections.

A.1. Magnetic field strength and discharge current variation

The V-I curves, obtained for the thruster configuration with a discharge chamber, are presented in Fig.3 and Fig.4. It can be seen that for the magnetic field values from 0 T to 0.035 T-0.053 T the curves have an increasing-decreasing trend. The presence of the magnetic field enhances this trend (see Fig. 3). Further increase of the magnetic field lead to a change in the V-I curve behavior, which shows a decreasing trend. The latter behavior started at the higher magnetic field values for the higher mass flow rates (See Fig.4).

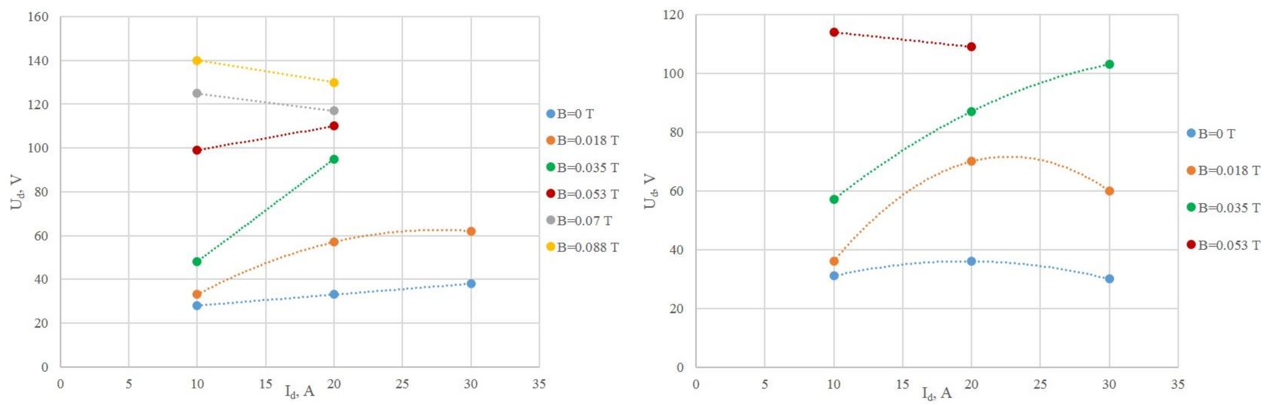
The discharge voltage increases with the increase of the magnetic field strength. This trend was also observed in other works on the rectangular shaped MPD thrusters [2, 3] and is typically attributed to the increase of the back electro-motive force.

The increase of the I_dB product causes a close to linear increase of the discharge voltage. The trend appears to be more dependent on the discharge current value than on the mass flow rate (Fig.5).



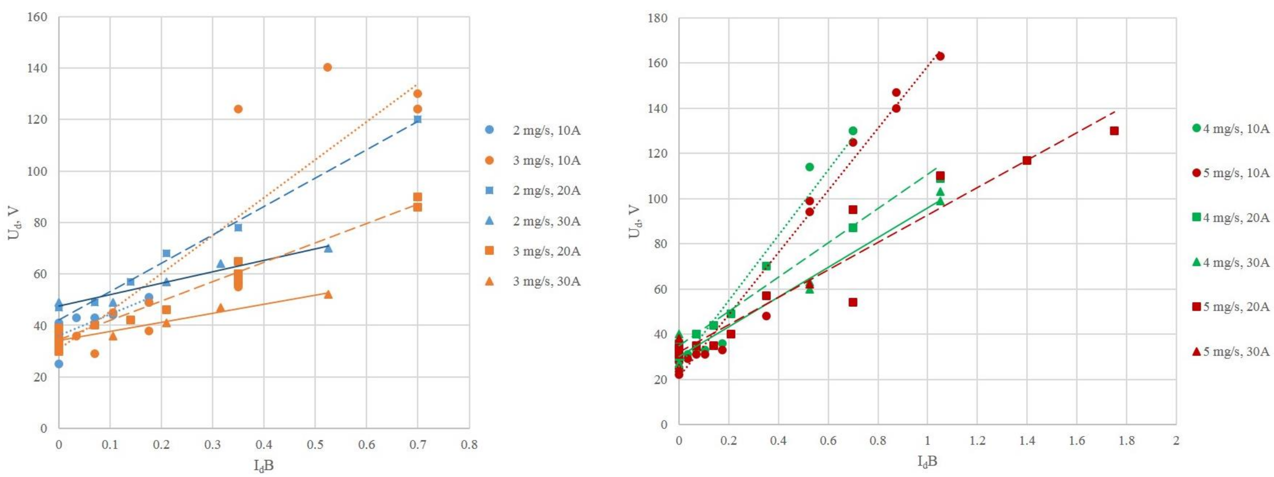
a) **b)**

Figure 3. V-I curves for different mass flow rates for a) B=0 T, b) B=0.018 T.



a) **b)**

Figure 4. V-I curves for different magnetic field strength values for a) m=5 mg/s, b) m=4 mg/s.



a) **b)**

Figure 5. Discharge voltage vs the product of discharge current and applied magnetic field strength for a) 2 mg/s and 3 mg/s, b) 4 mg/s and 5 mg/s.

The I_dB product seem to affect the thrust increment, creating an increasing dependence (see Fig. 6). However, the obtained data is not sufficient to establish a trend.

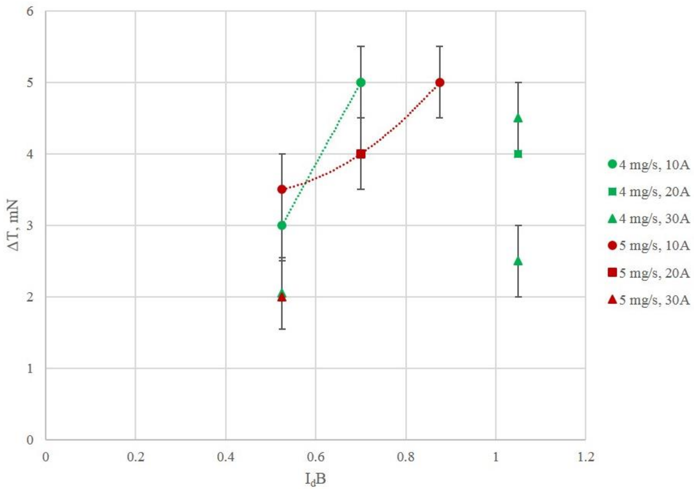
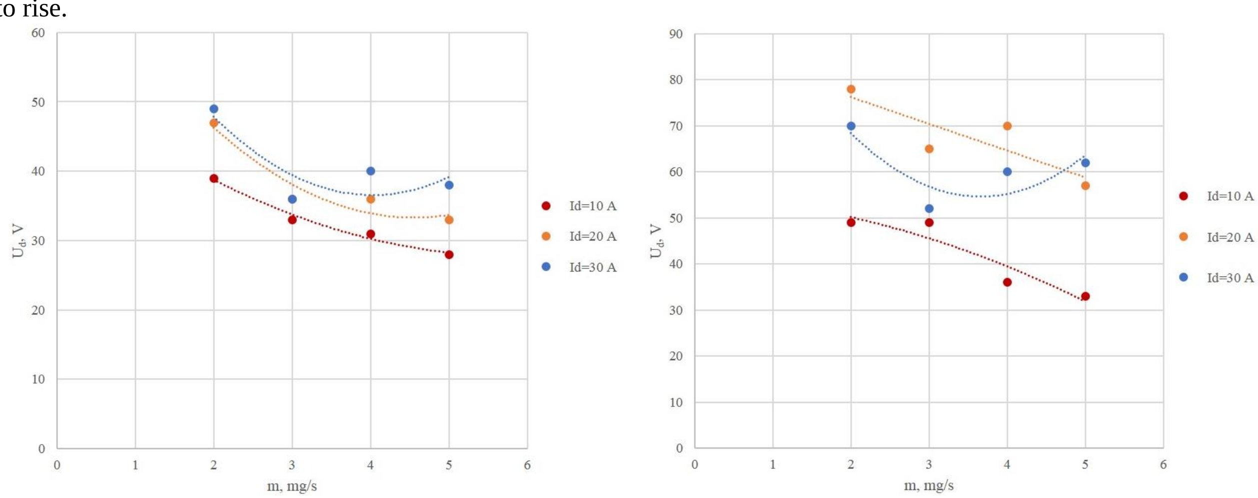


Figure 6. Thrust increment vs the product of discharge current and applied magnetic field strength for the mass flow rate of 5 mg/s and 4 mg/s.

A.2. Mass flow rate effect

The behavior of the $U_d(m)$ when the magnetic field is applied is similar to the one observed in [2] see (Fig.7 b)). However, we observed that the decreasing tendency of the curve is unrelated to the presence of the magnetic field (see Fig.7 a)) and consequently electro-magnetic effects. Higher mass flow rates correspond to higher pressure in the inter-electrode region and, as a result, lower breakdown voltage (first part of the Paschen curve). In the presence of the magnetic field, the $U_d(m)$ curves for discharge current of 10 A and 20 A are also decreasing, while the one of 30 A starts to rise.

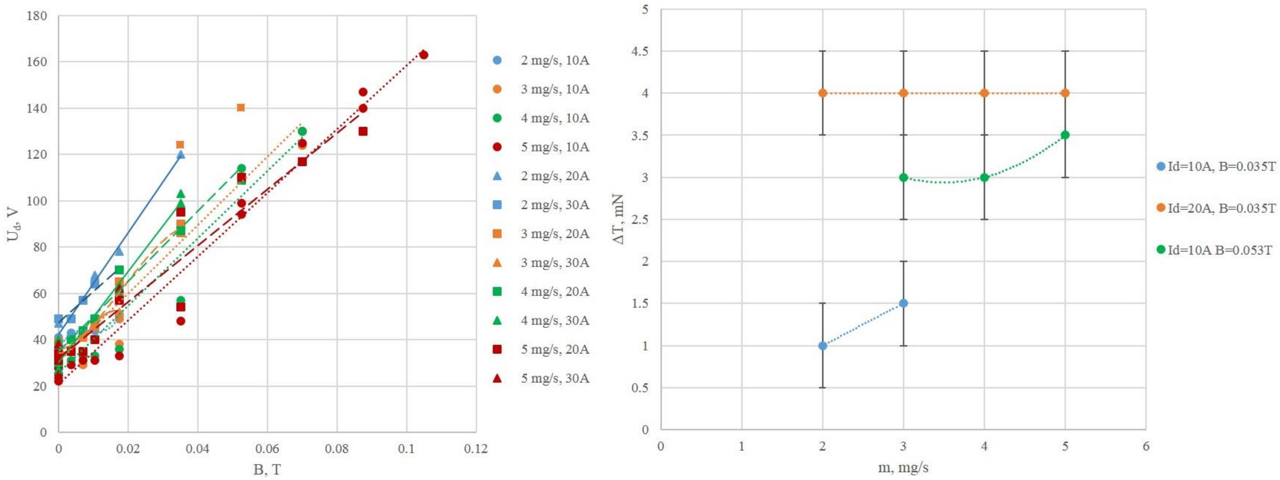


a) **b)**

Figure 7. U-I curves for different discharge current a) w/o applied magnetic field b) with B=0.018T.

Figure 8 a) illustrates that the discharge voltage increases sharper with the magnetic field strength at low mass flow rates with respect to higher ones.

Figure 8 b) and Fig. 9 show that the thrust increment due to the application of the magnetic field does not show any clear dependence on the mass flow rate, when evaluated for the same I_dB values, whereas the increase of the I_dB mainly leads to an increase of the thrust increment. For the same I_dB, the thrust increment rises also with the increase of the magnetic field strength.



a) **b)**

Figure 8. Performance with Xe: a) discharge voltage vs magnetic field strength, b) thrust increment vs mass flow rate.

Figure 8 illustrates that the discharge voltage increases sharper with the magnetic field strength at low mass flow rates with respect to higher ones. This phenomenon could be related with the increase of the cross-magnetic field electron mobility with the particle density increase. The magnetized electrons drift to the anode across the magnetic field in a way similar to the one in the Hall-Effect Thrusters. The drift occurs through the collisional mechanism. Therefore, the increase in particles density leads to an increase in the electrons cross-B mobility, reducing the discharge voltage increment.

Figure 8 b) and Fig.9 show that the thrust increment due to the application of the magnetic field does not show any clear dependence on the mass flow rate. The increase of the discharge current Id as well as the increase of applied magnetic field strength *B* clearly leads to an increase of the thrust increment (see Fig.8 b)). For the same I_dB, the thrust increment rises also with the increase of the magnetic field strength.

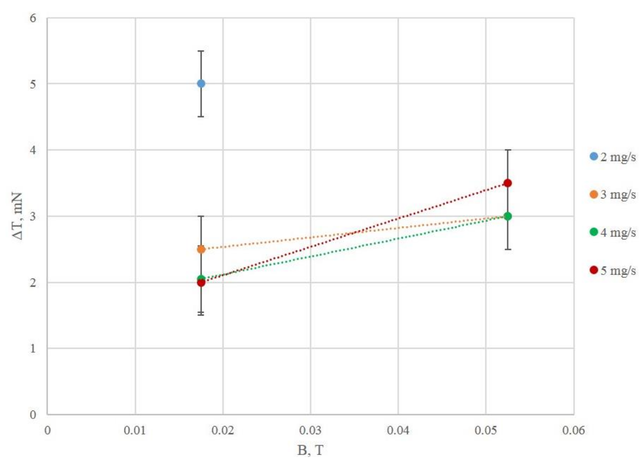
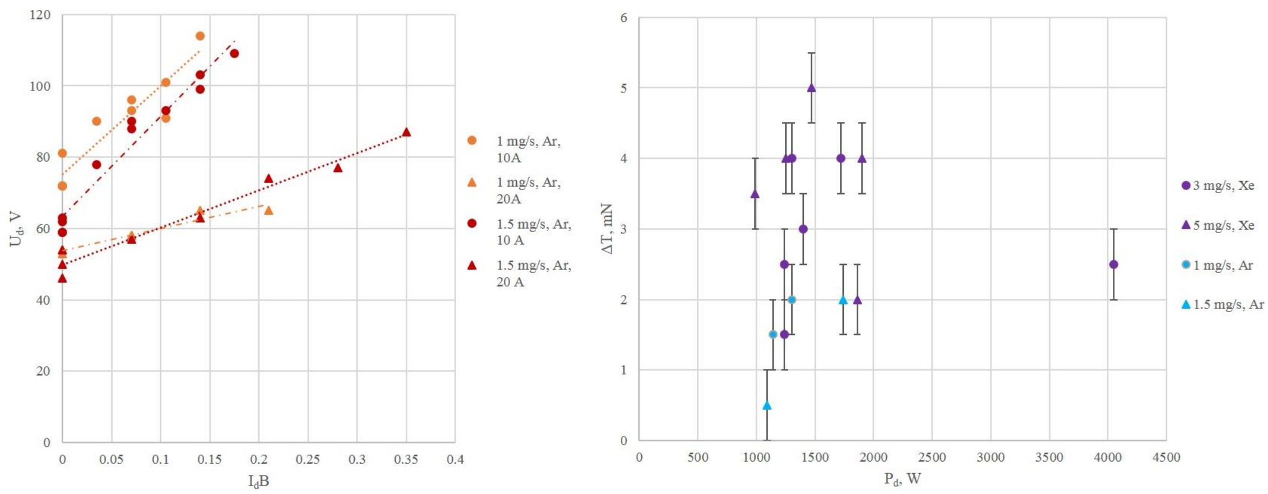


Figure 9. Thrust increment vs magnetic field strength for I_dB=0.053.

B. The performance with Ar

Argon is a typical choice for the MPD Thrusters and was also used in the experiments with the rectangular configuration [2-4]. SITAEL's HC60 was designed for operating with Xe and was previously tested also with Kr [5]. Within this test campaign, the HC60 was first time operated with Ar. We managed to achieve successful cathode ignitions at low mass flow rate values: 0.33 mg/s-1 mg/s.



a) **b)**

Figure 10. Comparison of performance with Ar and Xe: a) discharge voltage vs I_dB, b) thrust increment vs discharge power.

The discharge voltage, when operated with Ar tends to be higher than that with Xe. The thrust increment with the magnetic field application is lower than that of Xe. In Fig.10 and Fig.11. the performance with the two propellants are compared. The Xe mass flow rates, chosen for the comparison, correspond to the same particle number density as those of Ar.

Operation with Ar exhibits the same trends already observed with Xe: the discharge voltage for the lower discharge current tend to rise sharper with the magnetic field, than the one for the higher current. The mass flow rate does not affect the trend significantly.

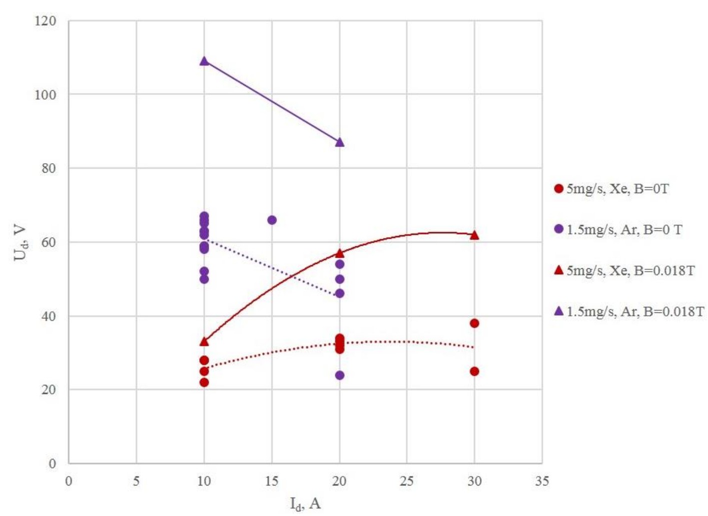


Figure 11. U-I curve for Ar and Xe with and without applied magnetic field.

The presence of the magnetic field significantly rises the I-V curve also for argon. However, the curves have a decreasing trend both with and without applied magnetic field. The decreasing I-V curve is characteristic for the arc-jets. In arc-jets this behavior is caused by the improvement of the ionization degree of plasma with increase of the discharge current. Due to a higher ionization potential of argon with respect to xenon (15.8 eV vs 11.7 eV), it could be that the argon in our tests was not fully ionized.

C. The effect of the discharge chamber

We performed the preliminary testing without the ceramic channel in order to investigate better the effect of the channel on the thruster performance. On the one hand, the existence of the channel may increase the plasma density in the discharge region and protect the test set-up from plasma. On the other hand, the channel walls are usually acting as an energy sink.

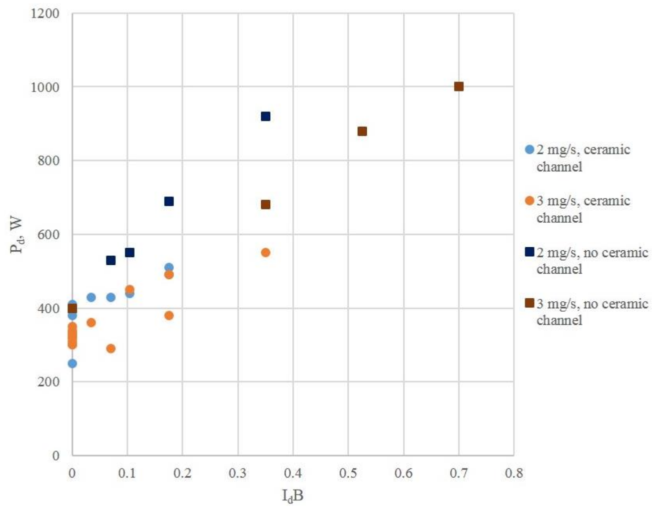


Figure 12. Discharge power vs I_dB for the operation with and without ceramic channel.

In Fig.12 the comparison test results are presented. The discharge voltage and consequently the discharge power appear to be slightly lower for the test set-up with the ceramic channel. The increased thermal losses to the walls would be reflected as an increase of the discharge voltage. Therefore, we can suppose that the effect from the plasma density increase is higher than that of the energy losses to the walls. However, this observation was made only for the low magnetic field values. For the magnetic field values above 0.5 A, the measurements with the ceramic channel were performed with the field applied in a stepwise manner. Whereas for the no-channel case the magnetic field strength was risen gradually. Therefore no direct comparison is possible for the I_dB values over 0.35 A·T.

V. Conclusion and Future Work

During this test campaign we performed a preliminary investigation of the Augmented-Field MPD thruster concept. The set-up was tested with SITAEL HC60 cathode operating with Xe and Ar propellants. At this stage the tests were held with the set-up operating at power levels below 4 kW. The results allowed us to verify the feasibility of the concept and understand the main criticalities for the further thruster development.

During the next step of the research and development activity, we are planning to rise the discharge power, targeting 30 kW range. Modifications of the thermal design and the introduction of an additional mass flow inlet are currently under investigation. An additional characterization with krypton propellant will be performed. An improvement of the thrust stand has been performed to allow the absolute thrust measurements for the MPD thruster.

Another point under investigation is the relative position of cathode tip with respect to the area of the maximal magnetic field intensity. The test set-up allows to vary the positions of both anode and cathode. The relevance of this feature will be investigated during the next test campaign.

The concept itself and the test results indicate that the performance improvement can be obtained maximizing of the magnetic field intensity in the acceleration channel. Therefore, for the possible implementation of the technology for space missions, generation of the high magnetic fields is necessary. The traditional solenoid coils would be ineffective due to their high mass. An application of the super-conductive magnetic coils could introduce an effective solution for this technological problem. Accordingly, thermal issues associated with the design of the high power MPD thrusters become of the critical importance and will be further investigated.

Acknowledgments

The authors wish to express their gratitude to Ugo Cesari, Carlo Tellini, Nicola Giusti, Luca Pieri, Massimo D'Urso, Ivan Andreani for their valuable assistance in preparing and performing the experimental campaign, and to Federico Cannelli for the support given during the setup of the facility. Fruitful discussions with Maryam Reza on the magnetic circuit design are gratefully acknowledged. A special thanks to Angela Rossodivita and Tommaso Misuri, who organized and supported the research activities on the augmented field MPD Thruster.

References

[1] M. Andrenucci, "Magnetoplasmadynamic Thrusters", *Encyclopedia of Aerospace Engineering*, 2010 John Wiley & Sons, Ltd. ISBN: 978-0-470-68665-2.

[2] A. Iwakawa, D. Nakata, H. Kuninaka, "Experimental Study of a Two-Dimensional Applied-Field Magnetoplasmadynamic Thruster", *Trans. JSASS Aerospace Tech. 8,* 2010.

[3] A. Sasoh, D. Ichihara, T. Enoki, S. Yokota, "Steady-State, Applied-Field, Rectangular Magnetoplasmadynamics Thruster Using Hollow Cathode", *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2012, AIAA 2012-4276.

[4] D. Ichihara, T. Uno, H. Kataoka, A. Iwakawa, A. Sasoh, "Operation Characteristics of Small-DC-Current, Applied-Field MPD Thruster", IEPC 2015-171, 2015.

[5] D. Pedrini, F. Torrini, J. Grassi, F. Paganucci, T. Andreussi, T. Misuri, & M. Andrenucci, "Development of Hollow Cathodes for 5 to 20 kW Hall Thrusters", IEPC-2017-364, 2017.