Experimental Assessment of a Passive Method for MHD Instability Suppression in MPD Thrusters

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Abstract: The paper deals with the experimental assessment of the effectiveness of introducing an insulating plate in the discharge chamber of an MPD thruster as a method of passively control the development of m=1 n=1 kink instability at critical regimes. A comparison of the performance in terms of electrical characteristics and thrust among a benchmark configuration (no plate) of a gas-fed MPD thruster and five different thruster configurations (plates with different shape and dimensions) is illustrated. Tests have been carried out with argon as propellant and with and without an externally applied magnetic field. Results indicate the plates have no significant or detrimental effects on the performance at low applied magnetic field. On the contrary, some plate configurations have shown to be effective at high applied magnetic field and current, by decreasing the arc voltage drop without significant effect on the thrust, with respect to the benchmark configuration.

I. Introduction

SINCE 2000, Alta/Centrospazio and Consorzio RFX have carried out extensive experimental campaigns of plasma diagnostics on gas-fed, applied field MPD thrusters. On the basis of measurements coming from electrostatic and magnetic probe arrays, the existence of critical regimes has been related to the onset of a basic magneto-hydrodynamic (MHD) instability, known as the (m=1; n=1) kink[1]. The onset of instability has been therefore linked to the Kruskal-Shafranov limit[1,2], as it is well known by the experience on fusion devices that the presence of a large MHD instability affects the current profile and locally modifies the density and temperature of the plasma. The subsequent use of an integrated system of electromagnetic, optical probes and ultraviolet tomography has given a further experimental evidence that the onset of critical regimes in MPDTs is related to the generation of large scale

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kink modes[3,4]. The plasma emissivity maps obtained with tomographic algorithm techniques, applied on the optical probe signals, have allowed to obtain a detailed characterization of the kink topological features at various thruster operating conditions. A localized out-of-axis region, more emissive than the background nearby, has been observed, displaced at different azimuthal angles, as soon as the critical conditions are reached, depending, for a given thruster, on mass flow rate and applied magnetic field. If an external magnetic field is applied, the emissive structure rotates azimuthally. Since the onset of kink instability is characterized by the deformation of a plasma column which is hotter and denser than the rest of the plasma, a large amount of the discharge current flows through the column itself: due to the distortion, large tangential component of the current (j_θ) will be present, and hence a significant axial magnetic field (B_z) is induced, which increases the applied field (paramagnetic effect), as experimentally observed. On the basis of theses evidences, different methods of suppressing and/or postponing the onset of the kink instability can be conceived. A simple method has been proposed in a previous paper, with some preliminary experimental results[5]. It consists in inserting in the inter-electrode region an insulating plate, extending in a meridian plane. The function of the plate is simple and brutal: it impedes, within a certain extension to be quantified, the deformation of the column due to kink instability. The experimental results indicated the effectiveness of the plate to this regard, with a thrust efficiency increase due to a reduction of the voltage required to sustain the discharge, without a significant modification of the thrust level with respect to a operation without the plate in critical condition. Moreover, a significant reduction of the paramagnetic effect was observed at the same conditions. In this paper, the experimental results obtained on a new thruster with different configurations of the insulating plate are shown. The effects of the geometry of the plate on electrical characteristics and thrust at different applied magnetic fields are herein discussed, while the effects on plasma plume properties are shown in another paper presented at this same conference[6].

II. Experimental Apparatus

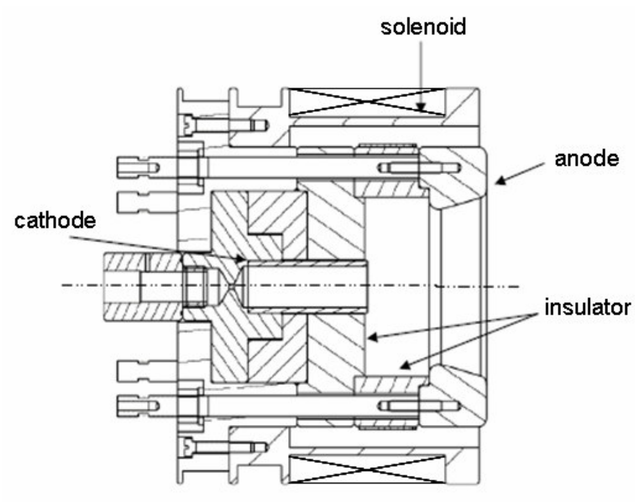

Fig. 1: a cross section of the applied field MPD thruster investigated.

The experimental apparatus is an axial-symmetric MPD thruster, with an external solenoid, illustrated in Fig. 1. It consists of a single channel hollow cathode, 16 mm in inner diameter, and of a ring-shaped anode, 62 mm internal and 108 mm external diameters. The electrodes, made of copper, are separated by an insulator made of MACOR®, consisting of a back-plate and a cylindrical component, on which two supports (not shown in the figure) are fixed, to allow the insertion of the plates for kink passive control. The coaxial solenoid allows a magnetic field up to 100 mT on the axis to be applied. The solenoid has a dedicated power supply, as illustrated in Ref. 7.

A first campaign has been carried out to assess the effect on thruster performance of plates with different shapes and to select the most effective configuration(s); seven configurations have been considered and five investigated, as illustrated in Fig. 3. In particular, it was decided to test plates occupying the total section of the inner plasma channel, or just a fraction of it, or even protruding outside of the thruster outlet, extending in the outer plasma plume. Hereafter the different geometries will be recalled with the numbering indicated in Fig. 3, while, with the number 0, we will refer to the standard MPD configuration, without any system for the control of plasma instabilities.

In this first campaign, the plates were made of plexiglass. In a second campaign (in progress) the plates selected are made of MACOR, in order to reduce spurious effects due to erosion/ablation of the plates.

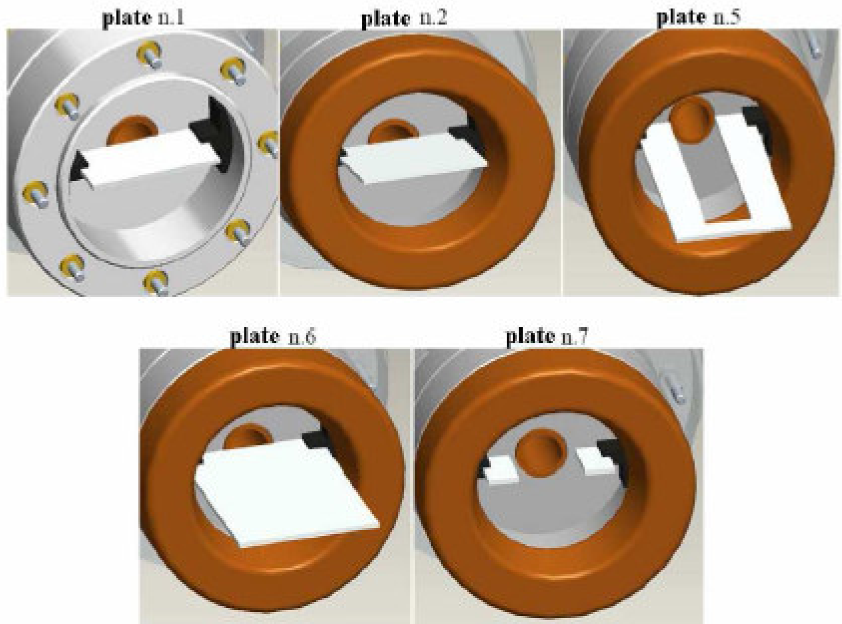

Fig. 2: Configurations for which test results are illustrated in the paper.

III. Test Equipment

The thruster is mounted on a thrust stand inside Alta's IV3 vacuum chamber, capable of maintaining a back pressure before and during the pulse in the 10^{-2} Pa range[7]. The electric power is supplied by a Pulse Forming Network (PFN), configured to supply quasi-steady current pulses 5 ms long. The propellant is injected through the hollow cathode by means of a fast acting solenoid valve, which provides gas pulses with long plateau after few milliseconds from valve activation. Prior the tests, mass flow rate and delay time have been measured with an uncertainty within 5% of the measurement by means of a calibration procedure, described in Ref. 8. An ignitron has been used to initiate the discharge when steady applied magnetic field and mass flow rate are reached. The arc current has been measured with a Hall effect current probe. To avoid anomalous discharge involving the vacuum chamber, the thruster electrodes are floating with respect to the ground and the arc voltage has been measured by measuring the potential of each electrode with respect to the ground by means of two high voltage probes. The arc voltage is then obtained by subtracting the cathode voltage signal from the anode voltage signal.

The thrust stand consists of two double pendulums, acting like a four–bar link, which leaves the thruster free to move only in the axial direction [7]. The hinges at the ends of the bars consist of thin phosphor bronze straps, that, for small displacements, act as virtual hinges with negligible disturbances to the mobility of the system. The suspension is fixed at the vacuum chamber by means of a stiff frame. The thruster is attached to the suspension by means of two supports. A proximity transducer is used to measure the mobile mass displacement. A computerized procedure has been developed to get the thrust input bit by knowing the mobile mass weight and measuring its motion law in a period around the shot. The input bits so obtained were then purged by spurious effects due to cold gas injection and the activation of the external magnetic field. These effects were previously measured by using the same procedure without the activation of the arc discharge. The method allows the net thrust impulse bit to be measured with an accuracy of about 10% of the value.

IV. Experimental Results

The various configurations investigated are herein compared in terms of electrical characteristics and thrust. A comparison in terms of plasma properties for the same tests is illustrated in Ref. 6. Tests have been carried out for a mass flow rate of 100 mg/s of argon and for four magnetic applied field conditions: 0 (i.e. self-field operation), 20, 50 and 100 mT (the values indicate the maximum magnetic induction field on the axis [7]). Each data point represents average values of the relevant quantities, measured for four-five shots at the same PFN charging voltage. For each shot, a value of arc voltage and current were obtained as an average on a window 100 microseconds long taken in the middle of the pulse. Thrust is obtained by dividing the measured thrust impulse bit time the pulse duration, and thus the value represents an average thrust for each shot. Error bars include both standard deviation and measurement uncertainty. For arc voltage measurements, the oscillation amplitude is not considered in the error bar (see Ref. 6 for this issue). PFN charging voltage range has been chosen in order to span arc currents between 1.5 to 4.5 kA. As shown in Tab. 1, the arc current range allows critical regimes to be investigated for all of the applied magnetic field condition.

Applied Magnetic Field (mT)	Critical Current (kA)
0	2.3
20	2.5
50	2.1
100	1.5

Tab. 1 Critical current for the MPD thruster investigated (benchmark configuration) at 100 mg/s of argon, in accordance with Ref. 1 and 7.

Figs. 3 and 4 illustrate the electrical characteristics and thrust of the MPD thruster without plates (benchmark or configuration 0), as a function of the applied magnetic field. Tests carried out on the various configurations have indicated the plate can have either no significant, beneficial or detrimental effects on the performance, with respect to configuration 0. In the following the results obtained with the configurations having led to either no significant or beneficial effects are reported. A configuration with performance worse than the benchmark is also illustrated.

Operation at low applied magnetic field. In Figs. 5 and 6 a comparison in terms of electrical characteristics and thrust respectively is made among conf. 0 and 1, 5 and 7 for a self-field operation. In Figs. 7 and 8 an analogous comparison is made (conf. 0 vs 1, 6, 7) for 20 mT of applied field. Within the accuracy of the measurements, in both cases, no significant effects of the plates on electrical characteristics as well as thrust have been observed.

Operation at high applied magnetic field. At 50 and 100 mT, some plate configurations have shown to be effective at high current levels, by reducing significantly the arc voltage drop at a given current with respect to conf. 0 operation, without significantly change in the thrust. The comparison is illustrated in Figs. 9 and 10 for 50 mT and in Figs. 11 and 12 for 100 mT. Other configurations (not reported in this paper) have proven to effectively reduce the arc voltage drop, but, at the same time, to reduce the thrust to such an extent that no net improvement of the performance can be claimed. This behaviour has been observed especially for plates extending out of the discharge chamber. In some cases, as illustrated in Figs. 13 and 14, the plate insertion has had a negative impact on the performance, both in terms of electrical characteristics and thrust.

At the end of the tests, the plates have not presented visible signs of erosion and/or ablation. On the contrary, sputtered material coming from the cathode and char deposition due to the oil of the vacuum chamber booster pumps have been observed on the plate surface and on the other insulating components.

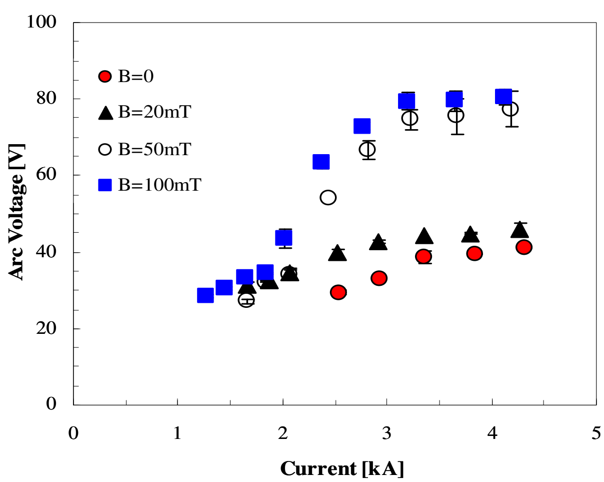

Fig. 3: Configuration 0 electrical characteristics as a function of the applied magnetic field (100 mg/s of argon).

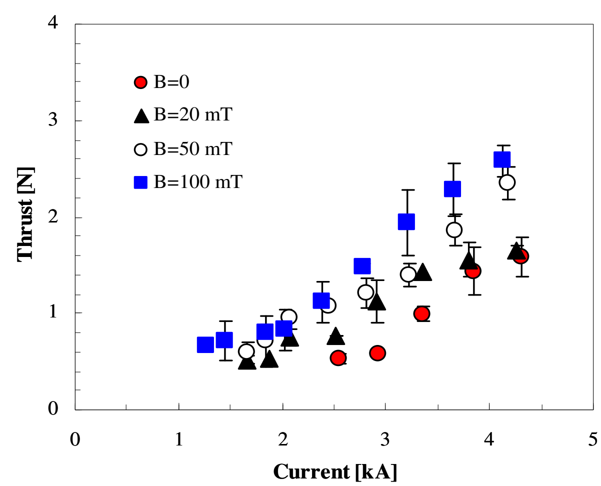

Fig. 4: Configuration 0 thrust as a function of the applied magnetic field (100 mg/s of argon).

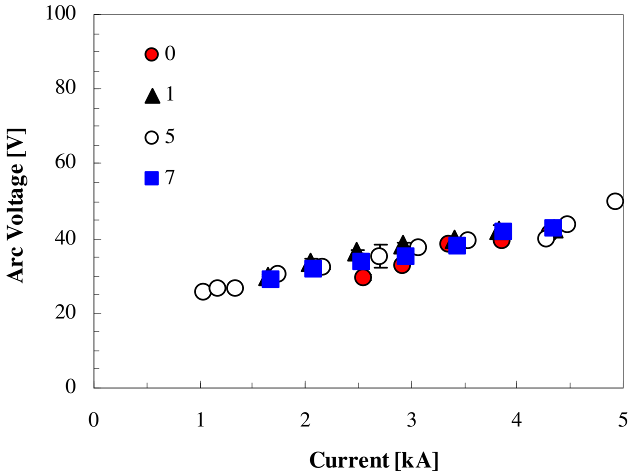

Fig. 5: Electrical characteristic comparison without applied magnetic field, 100 mg/s of argon. Conf.0 vs Conf. 1, 5 and 7.

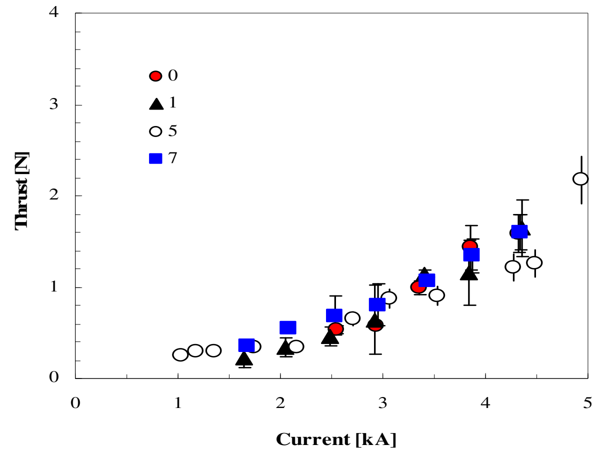

Fig. 6: Thrust comparison without applied magnetic field, 100 mg/s of argon. Conf.0 vs Conf. 1, 5 and 7.

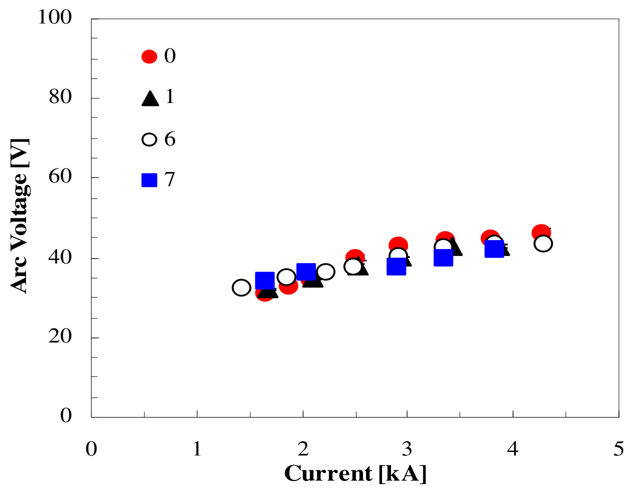

Fig. 7: Electrical characteristic comparison, 20 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1, 6 and 7.

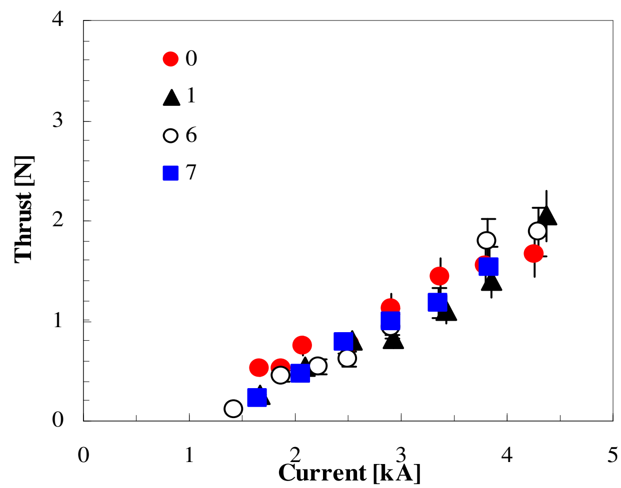

Fig. 8: Thrust comparison, 20 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1, 6 and 7.

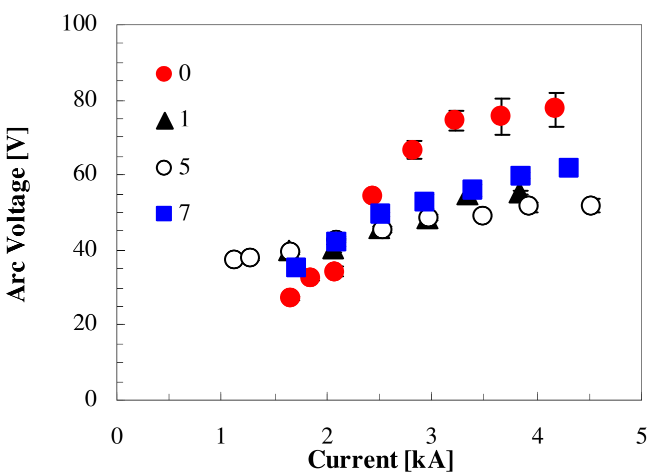

Fig. 9: Electrical characteristic comparison, 50 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1, 5 and 7.

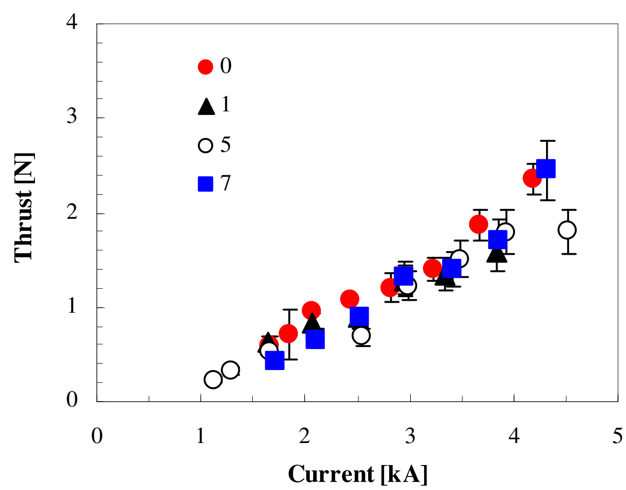

Fig. 10: Thrust comparison, 50 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1, 5 and 7.

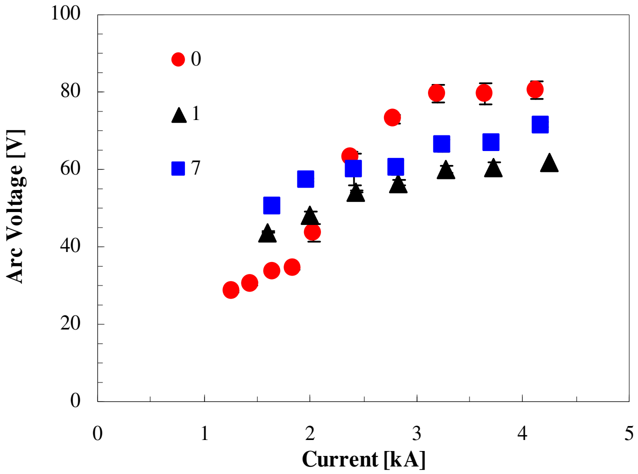

Fig. 11: Electrical characteristic comparison, 100 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1 and 7.

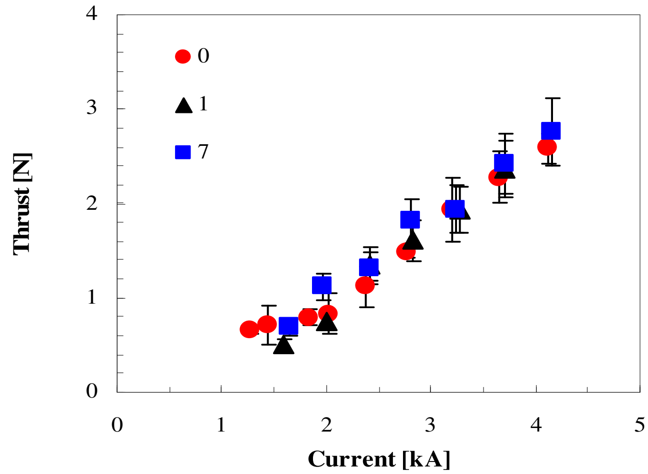

Fig. 12: Thrust comparison, 100 mT, 100 mg/s of argon. Conf. 0 vs Conf. 1 and 7.

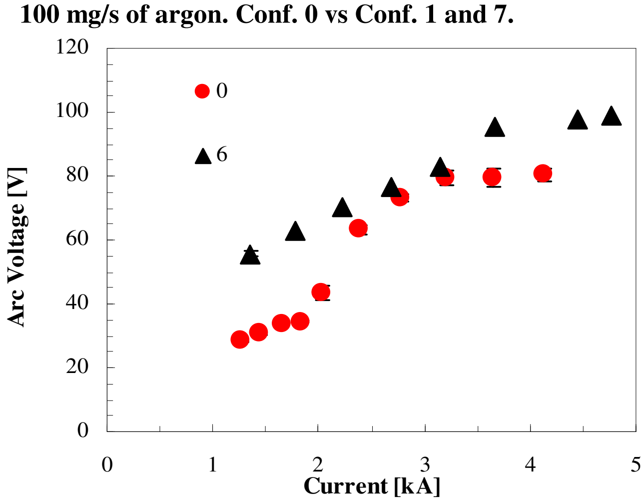

Fig. 13: Electrical characteristic comparison, 100 mT, 100 mg/s of argon. Conf. 0 vs Conf. 6.

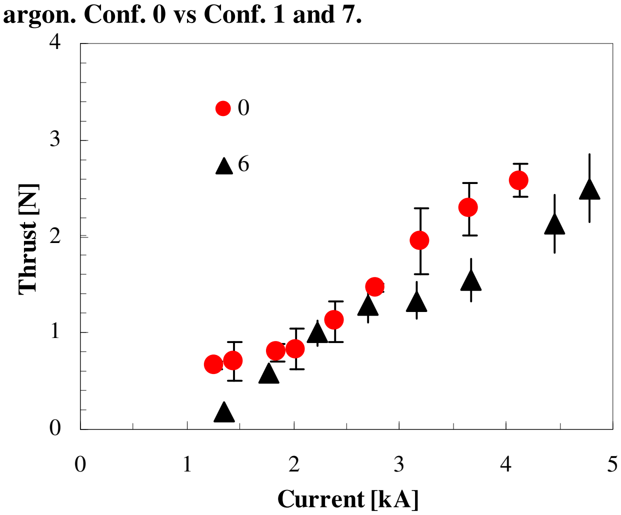

Fig. 14: Thrust comparison, 100 mT, 100 mg/s of argon. Conf. 0 vs Conf. 6.

V. Concluding Remarks

The results above illustrated indicate the use of insulating plates inserted in the discharge chamber of MPD thruster as method for the suppression and/or control of MHD instabilities has an impact on the overall thruster performance which depends on thruster operation parameters and the geometry of the plate itself. At zero or low applied magnetic field, the plates, independently on the shape and dimension, seem to be ineffective in changing thruster performance, neither improving nor reducing arc voltage drop and thrust at a given current with respect to the thruster without plates. On the contrary, at higher applied magnetic field (50 and 100 mT), some plate configurations have proved to reduce considerably the arc voltage drop beyond the critical current, without changing the thrust level. The influence of spurious effects, like ablation/erosion from electrodes, insulators and plates and vacuum condition remains to be assessed. To this purpose, the entire experiment has been recently transferred in the Alta's IV4 vacuum facility, equipped with turbo-molecular and cryogenic high vacuum pumps, which will guarantee cleaner vacuum condition during testing. Moreover, some of the plates which demonstrated better performance have been manufactured in MACOR, in order to reduce erosion/ablation issue, and will be tested in the following months. New tests will be performed with an improved plasma diagnostics, including spectrometry to detect spurious contribution to mass flow rate. Results will be presented in a next paper.

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