Experimental Test Campaign of Gas-fed Steady State Applied-Field Magnetoplasmadynamic Thruster SX3

IEPC-2013-251

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 - 10, 2013

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Abstract: **The AF-MPD thruster SX3 has been designed and built in the framework of ESA project for operational arc power of 100 kW in steady-state mode and Argon as propellant in 2011. The thruster has been successfully put in operation in summer 2012 with modified applied-field coil of AF-MPD ZT1 thruster. However, due to relatively small applied-field coil size the B-field geometry was not optimized for SX3 device, leading to non-stable operational conditions and significant arc wall chamber interactions. There for a new applied-field coil has been designed and build for SX3 thruster in 2012-2013. The new coil features less divergence of anode *B* field lines leading to more slender magnetic field geometry. Characteristic and comparison of new applied-field coil with previous ZT coil is presented in this paper. Additionally an overview is given of current experimental setup, major difficulties of operation of steady-state devices and an overview of current and future experimental investigations at IRS laboratory.**

Nomenclature

AF	=	Applied-Field
B	=	Magnetic flux density
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt
I_{sp}	=	Specific impulse
ISRU	=	In Situ Resource Utilization
LiLFA	=	Lithium Lorentz Force Accelerator
MPD	=	Magneto-Plasma-Dynamic
MPDT	=	Magneto-Plasma-Dynamic Thruster
T	=	Tesla
TRL	=	Technical Readiness Level
SF	=	Self-Field

I. Introduction

Steady-state gas-fed applied-field magnetoplasmadynamic thrusters feature high exhaust velocities, high thrust density and are suitable for interplanetary missions with a power level of up to MW. The achieved thrust efficiencies of steady-state AF-MPD thrusters are typically between thirty and forty percent.[1-4] State of the art applied-field steady-state magnetoplasmadynamic thrusters have demonstrated good performance by reaching thrust efficiencies up to 40 % with Argon and up to 50 % with Lithium as propellant.[1-3] The respective exhaust velocities vary depending on mass flow rate of used propellant in a range of 25-50 km·s^{-1}. However, Hydrogen driven devices can even reach exhaust velocities up to 70 km·s^{-1}.[5]

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Compared to the Self-Field MPD thrusters, which depend on high current levels, the AF-MPD thrusters can operate with higher efficiencies at discharge powers of 100 kW. Because of these capabilities AF-MPDTs are of interest for high power automatic cargo transport applications, for manned missions to Mars as investigated in Ref. 6, and for mission scenarios to moons of Jupiter and Saturn. However, for feasibility of practical applications thrust efficiencies greater than 40 % and exhaust velocities of 25-50 $km \cdot s^{-1}$ will be required.

Compared to other electric propulsion concepts the technical readiness level of applied-field MPD thrusters (TRL 4) is relatively low. This should be considered by comparing to other electric propulsion systems with respect to further understanding, optimization and improvements of AF-MPD devices. There are a few major challenges, which need to be solved. These are: design and scaling criteria, life time of the cathode, applied magnetic field distribution, thrust efficiency improvement, cooling, and PPU development.

Basically, two different steady-state AF-MPDT design trends tend to stand out through their operational regimes, high current driven devices such as LiLFA,[4,7,8] and high magnetic flux density such as DLR's X16 thruster.[1,2]

The use of high applied magnetic fields comes with high thermal losses and power consumption especially with increasing anode radius and is only justified by application of superconducting materials for applied-field coil. The instabilities that appear during operation at high magnetic flux densities need to be considered and analyzed in future activities. However, the performance of DLR's X12 and X16 thrusters is promising with respect to thrust efficiency and use of gaseous propellant such as Argon, which can be extracted via ISRU from Mars atmosphere.[9]

In contrast to high current driven Applied-Field MPD thrusters based on DLR's X16 accelerator the institute for space systems (IRS) approaches mainly a high magnetic flux density and low discharge current gas-fed concept.[10] The goal of current research at IRS is the increase of the thrust efficiency by improving means for characterization of operative parameters, characterization of electrode losses and plasma. The intent of this paper is to present current experimental activities at institute of space systems on investigated 100 kW steady-state gas-fed AF-MPD SX3 thruster and an outlook of further AF-MPD activities at IRS.

II. Experimental Setup

The experimental investigations on Applied-Field MPD thrusters take place at IRS laboratory, which has access to high power facility made by SIEMENS that can provide up to 6 MW with DC current of up to 48 kA at 125 V or up to 6 kV at 1 kA.[11] For operation of an AF-MPD thruster 2 separate current controlled circuits can be adjusted for applied-field coil and the thruster. During experiments on AF-MPD SX3 thruster the power distribution was set up to 1000 A at 1000 V and the circuit of the coil was limited to 1000 A at 500 V. Further increase in current levels in order to achieve operational regime with 100 kW arc power for future experiments will require additional current cables and changes to experimental assembly on thrust balance and current throughput. Current evaluation was done by measuring drop voltage up to 60 mV on predefined resistance of $1 \cdot 10^{-4}$ Ohm for the thruster and $4 \cdot 10^{-5}$ Ohm for the coil. Discharge and resistance drop voltage were measured by house made voltmeter. For higher current levels at 100 kW arc power replacement of predefined shunts for current measurement will be required. This will however decrease measured accuracy of arc and coil current.

The vacuum facility consist of BA 360 rotary vane pump, multistage rotary vane pump RV 560, 3 roots pumps of type MTP 5000, and one large Alcatel roots pump. The total throughput of the vacuum facility is about 200 000 $m^3 \cdot h^{-1}$ at approximately 10 Pa tank pressure and minimal achievable pressure of 0.5 Pa.[11] All experiments on AF-MPD thrusters at IRS take place in stainless steel double wall water cooled vacuum chamber with diameter of 2 m and 5 m length. Monitoring of vacuum chamber's pressure is done by Pfeiffer PKR 251 and BOC Edwards WRG-S wide range pressure gauge.

The anode and cathode propellant distribution is provided by a pair of Bronkhorst F-201CV flow controllers with up to 10 $mg \cdot s^{-1}$ of Argon each. For experiments with arc power above 30 kW both flow controllers will be replaced with better suited flow rate range in next test campaign.

For the cooling purpose high pressure pumps with closed cycle can provide up to 20 bar high pressure cooling water for the thruster and coil assembly. The chamber wall, heat shield and other equipment are cooled by low pressure cooling water with up to 4 bar. During last test campaign on AF-MPD SX3 thruster, high pressure water distributor provided cooling water for modified ZT coil assembly and SX3 thruster.[10] This has been changed to 3 separate high pressure water distributors allowing better adjustment of the cooling for new applied-field coil, anode, and the structure of SX3 including cathode cooling. However, due to the amount of cooling pipes it is very difficult to identify small water leakages, which can increase local pressure up to some Pascal.

Characterization of *B* field will be performed by Hall probe model 5180 from F.W. Bell without operating the SX3 thrusters by applying only the coil current. Structural and cooling water temperatures are monitored by K and J-type thermocouples, and PT100 resistance thermometers. Compared to previous test campaign the data acquisition system and measuring program were replaced leading to increase of measuring frequency from 0.3 Hz up to average measuring frequency of 15 Hz.

A. SX3 Thruster

The SX3 thruster was developed as actively cooled steady-state and gas-fed AF-MPD accelerator featuring a modular design allowing this way an implementation of different electrodes to the main housing of the thruster (see Fig. 1). Due to active water cooling the thruster can be operating in a wide power range in steady-state mode for a long period of time. Active water cooling allows also an evaluation of heat losses of the thruster and a better characterization for future development of engineering AF-MPD thruster models.

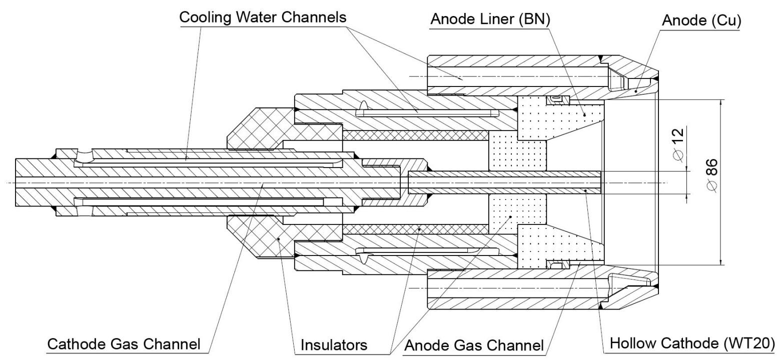

Figure 1. Sectional view of AF-MPD SX3 thruster.

Cathode liner, anode, and main housing are made of Copper. Insulator materials are Boron Nitride, Alumina, and PEEK. The latter one replaced PVC back insulator from previous test campaign due to heat damage on connection surface to alumina insulator tube.[10]

Propellant injection is separated to the cathode and anode gas allowing better optimization of operational regime for higher thrust efficiency and lower anode losses. Furthermore, the anode gas injection has axial direction and can be adjusted via replaceable injector with a possible swirl direction.

Alternative cathodes can be implemented with a maximum cathode diameter of 24 mm via copper adapter, which needs to be electron welded with the cathode. However, the cathode centering insulator made of Boron Nitride should be replaced for each specific cathode diameter. The position of current single channel hollow cathode with outer diameter of 12 mm can be displaced in axial direction allowing a variation of effective cathode length. A passively cooled Tungsten anode has been considered for the future activities and may be developed and manufactured for long term of testing procedures.

B. Applied magnetic field coil

The initial test campaign of AF-MPD SX3 thruster has been performed with modified coil from AF-MPD ZT1 thruster. Due to higher inner diameter of the SX3 thruster the inner segment of ZT coil was removed and the segments of the coil were displaced up to 45 mm relative to each other in axial direction resulting a flared version of applied-field coil (see Fig. 2).[10] The modified ZT coil was intended to be a preliminary solution for first ignition tests of SX3 thruster.

However, due to interaction with vacuum chamber and strong divergence of anode *B* field lines of modified ZT coil, a new applied-field coil has been designed and manufactured at IRS in order to improve the path of discharge arc and operation of the thruster. Figure 4 shows the new coil assembly for SX3 thruster. The new assembly consists of 7 separated cooling water loops, which are made of copper pipe (10/8 mm outer/inner diameter) and are connected in series electrically. However, the separation of the cooling allows higher current levels up to 1500 A (0.3 T), but decreases homogeneity of the *B* field near the coil housing.

The coil contains about 70 turns and is 325 mm in inner diameter. In this case it can generate a good trade-off between slender *B* field geometry with respect to anode field lines and achievable magnetic flux density. A simulation with FEMM software tool (see Ref. 12) of new applied-field coil and comparison to previous modified ZT1 coil is shown in Fig. 3. An experimental characterization of the coil will be presented in the future.

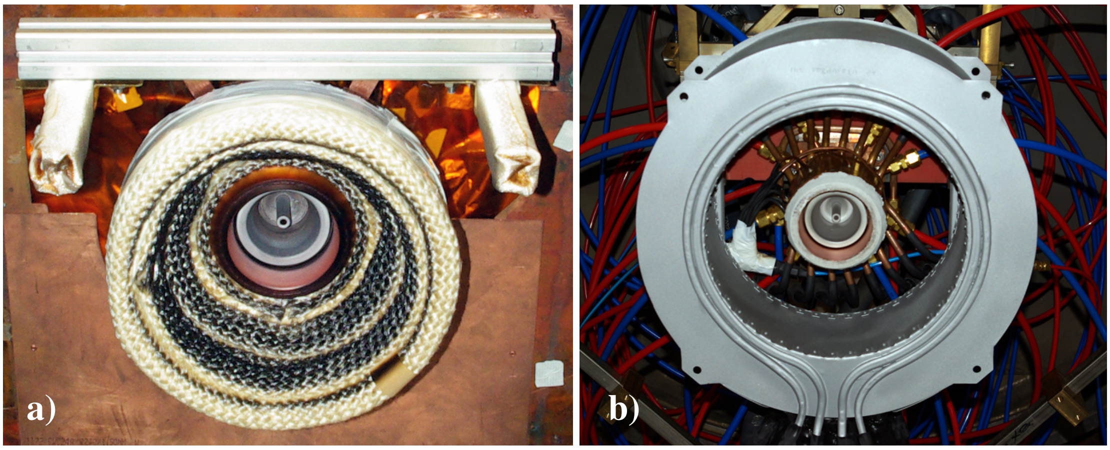

Figure 2. Modified applied-field coil from ZT1 thruster a) and new coil for SX3 thruster b).

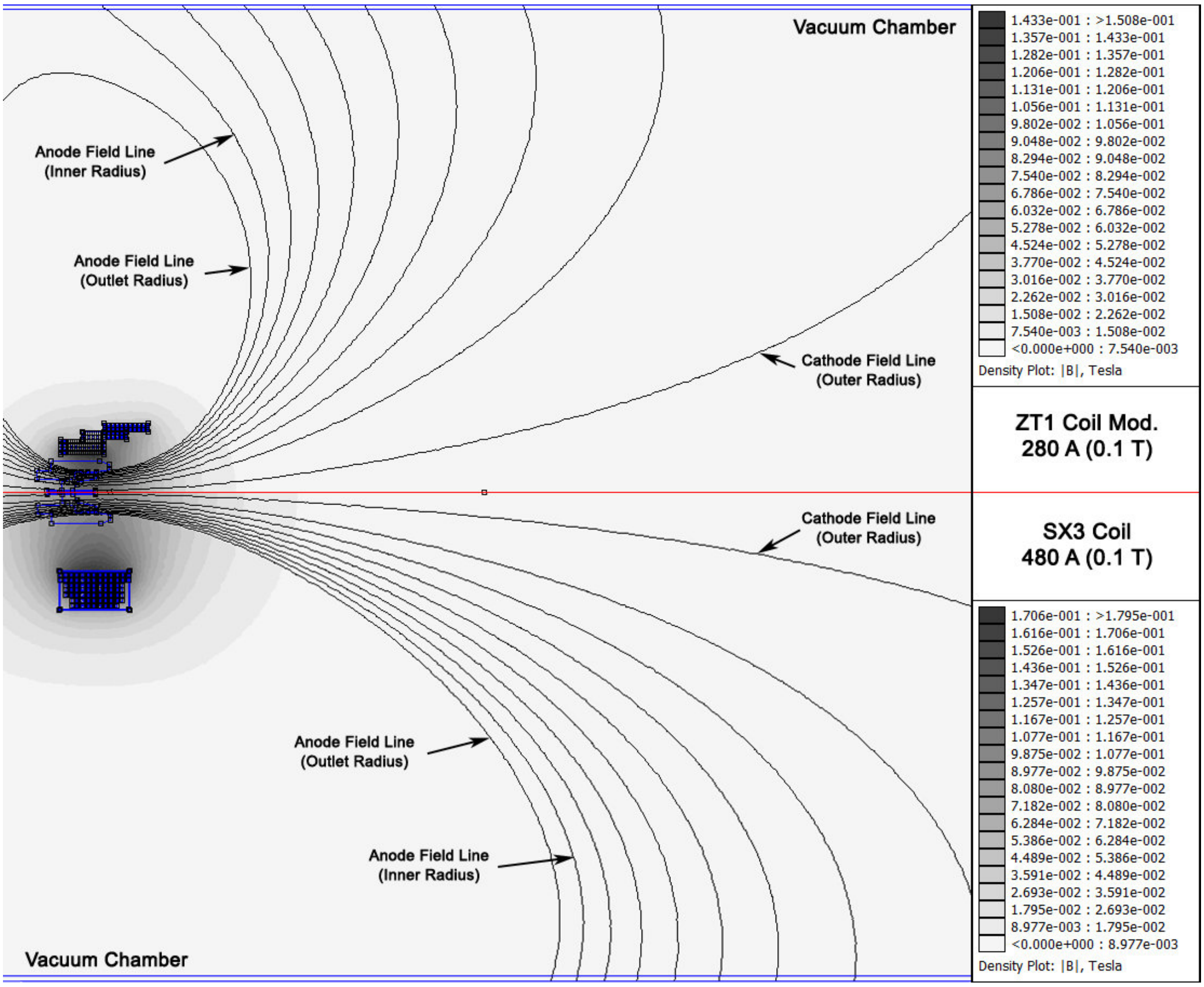

Figure 3. Comparison of *B* field geometry between modified ZT1 coil from previous test campaign (top plot) and new applied-field coil for SX3 thruster (bottom plot), both simulated with FEMM software tool (Ref.12).

C. Thrust balance

For thrust measurements the thruster and applied-field coil are mounted on parallelogram thrust balance, which is placed inside the vacuum chamber (see Fig. 4). During operation the thrust can be measured by KD40S force sensor allowing theoretical measurement accuracy of ±12.5 mN.

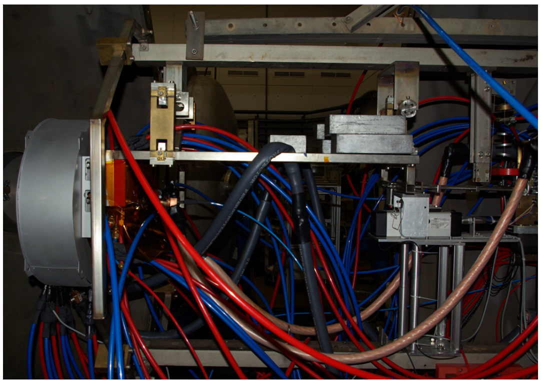

Figure 4. Parallelogram thrust balance.

Nevertheless, there are few influences, which make thrust measurements very difficult and less accurate. These influences are: electromagnetic effects, thermal expansion, damping, and oscillations caused by high pressure water pumps. The latter effect has relative high amplitude and can be calibrated out by data analysis. Electromagnetic effects can be characterized by short circuit measurements and need to be performed for each operational condition.

The drift of measured signal caused by thermal expansion is specific for each operational condition and its characterization very time-consuming.

Therefore, during experiments the thruster needs to be operated in steady-state mode till the stationary thermal conditions are reached and drift can be neglected.

Afterwards the force sensor will be calibrated by 3 predefined masses of 0.028 kg each allowing to a certain point a determination of non-linearity of thrust balance behavior and damping respectively affected by current and cooling water supply. After shut down the arc the force difference can be measured. Finally the data will be analyzed and thrust evaluated.

III. Current experimental test procedures

In initial test campaign SX3 thruster was put successful in operation with modified ZT1 coil in 2012. The thruster has been operated at arc powers up to 40 kW with a total duration of 3600 seconds.[10] During preliminary thrust measurements SX3 achieved thrust efficiency up to 12 % and thrust of 347 mN at 25 kW arc power, arc current of 200 A, magnetic flux density of 0.1 T and 20 mg·s^{-1} (10+10) mass flow rate with Argon as propellant.[10] However, visual fluctuations of the plume in steady-state operation with approximated frequency between 0.5 and 3 Hz depending on applied magnetic field strength have been observed (see Fig. 6). The fluctuation frequency increased with magnetic flux density and arc current.

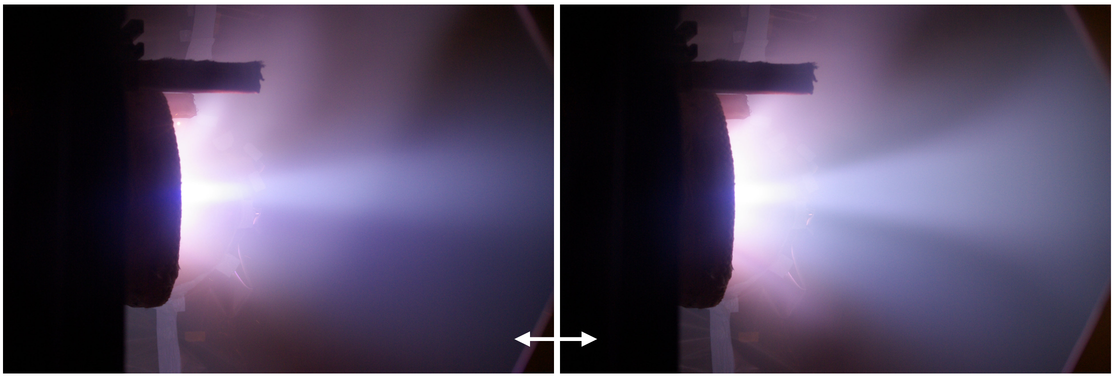

Figure 6. Photographs of visual plume fluctuations from previous test campaign in 2012 with modified ZT1 coil and partial insulation of vacuum chamber with Kapton® film.[10]

The variation of mass flow rate showed almost no effect on plume fluctuations and need to be investigated in the future with the new applied-field coil. The presence of significant arc voltage fluctuations has been decreased by partially insulation of vacuum chamber with Kapton® film making preliminary thrust measurements viable. These observations imply an interaction between discharge arc and vacuum chamber caused by strong divergent applied-magnetic field of modified ZT coil, since the partial insulation of vacuum chamber significantly improved the operation of the thruster.

After assembly of new SX coil and implementation into current setup the thruster has been put in operation and tested in arc power range of 30-45 kW with coil current of 350 A. The ambient pressure of approximately 0.6 Pa during operation was similar to previous tests. Argon mass flow rates and mass flow rate ratio of 20 mg·s^{-1} (10+10, anode + cathode) remained the same as in previous tests in 2012.[10] SX3 has been tested with arc current range of 300-400 A, whereas in previous test the arc current range was about 175-225 A.[10] In the case of magnetic flux density the current tests have been done under lower conditions below 0.1 T compared to 2012 test campaign with 0.1 T and 280 A. Nevertheless, in contrast to previous test campaign with modified ZT coil, the SX3 thruster showed stable steady-state operation and significant improvement of operation without partial insulation of vacuum chamber. An exemplary voltage current characteristic of the arc after ignition phase is shown in Fig. 7.

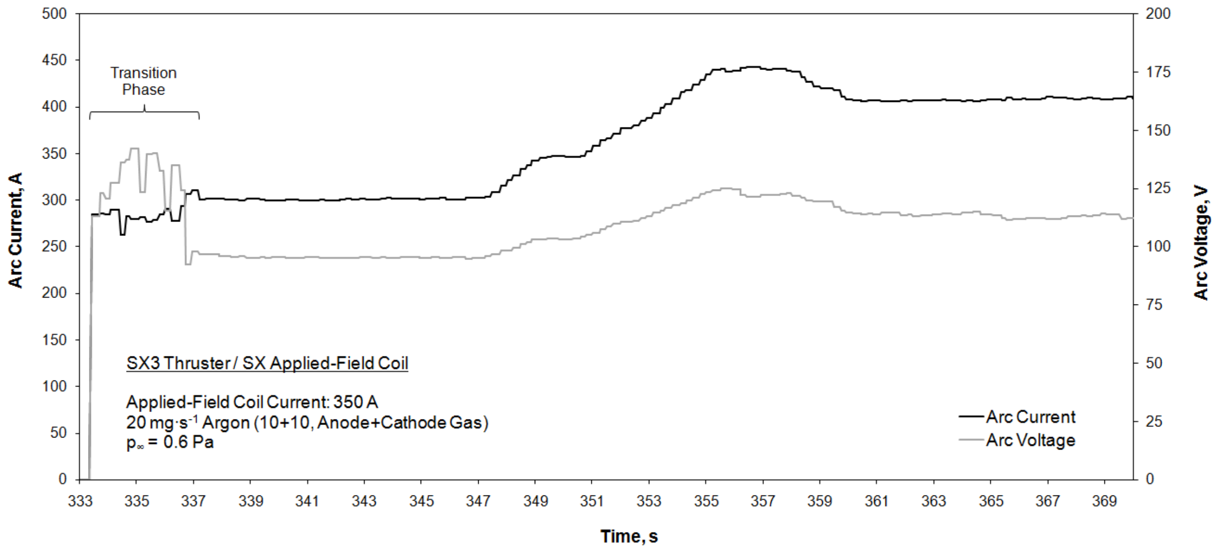

Figure 7. Raw signal of arc current and voltage after ignition with transition phase to visual flared plume shape and stable operation in steady-state mode (new applied-field coil).

During ignition phase the visual shape of the plume changed right after short transition phase of approximately 3.5 seconds from visual so called plasma lance to flared type plume shape (see Fig. 8). The visual plasma lance type of the plume is very typical for AF-MPD thrusters with separated gas injection and single channel hollow cathode like in case of DLR's X16, and IRS AF-MPD ZT1 thruster.[1,10,13] This implies a possibility of non-optimized operational conditions of current setup. A possible interaction of arc with conductive vacuum chamber's wall can be still present and affect the operation of the arc.

Compared to previous test campaign the cathode shows typical erosion of the cathode shown in Fig.9. Due to undesired discharges occurred during ignition phase a few times, water and gas leakages can be still present. However, the insulation of back parts of the thruster is very important for successful ignition and operation and is currently under improvement for the next tests. Because of the new applied-field coil the old heat shield assembly can't be used anymore. This problem decreases experimental times drastically and will be fixed in the future. A partial insulation of vacuum chamber wall and operation with the new coil has been not tested yet and will be possibly investigated in further proceedings. Additionally a smaller anode diameter is also in consideration, since in same *B* field geometry the anode field lines of smaller anode tend to diverge less.

These results show good evidence that operation of thruster has been significantly improved by changing the coil geometry to more slender *B* field geometry. Additionally it implies the importance of optimization process of magnetic field geometry with respect to electrode geometry and also considering vacuum chamber's size. Furthermore, it implies that usual instabilities which occur in operation of AF-MPD thrusters may be affected not only by magnetic flux density but also by applied-field geometry with respect to anode radius and anode field lines respectively.

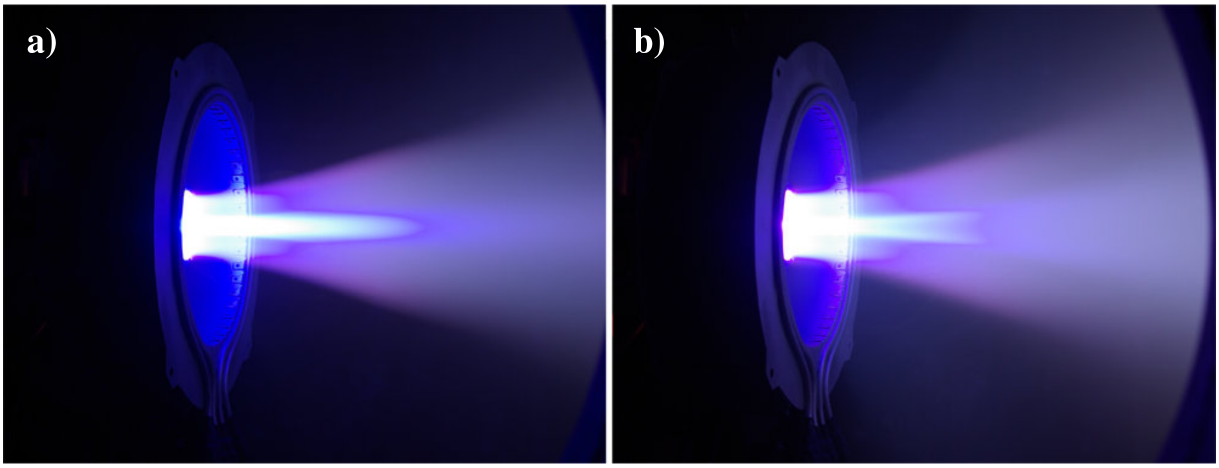

Figure 8. Visual plume photographs of transition from regime with lance type plume shape a) to final more stable operation with flared plume shape b).

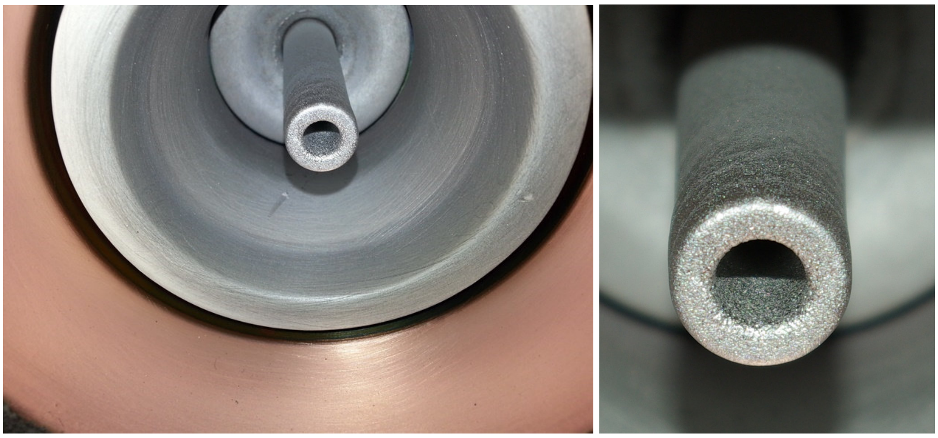

Figure 9. Single channel hollow cathode after last experiments.

IV. Conclusion

The experimental results presented in this paper show an overview of the current status of experimental investigations on SX3 thruster below 50 kW arc power level. Due to more slender *B* field geometry the operation of SX3 thruster has been significantly improved without partial insulation of vacuum chamber's wall, whereas in previous tests with modified ZT1 coil a partial insulation of vacuum chamber was required in order to operate the thruster by significant reducing of arc voltage oscillations. The improvement of the arc operation with new applied-field coil to stable steady-state operation shows the importance of *B* field characteristics with respect to electrodes geometry and also to vacuum chambers size.

However, further improvements of test setup will be required for future experiments. Near term priorities of further investigations of applied-field magnetoplasmadynamic thrusters at Institute of Space Systems in Stuttgart include investigations of stability in steady-state operation and also transition effects, possible interaction with the vacuum chamber via measurements of parasitic currents and possible implementation of insulation via Kapton® film, extensive research on influence of operative parameters, possible implementation of smaller anode diameter, and operation of SX1 thruster downscaled version of SX3 thruster.

Acknowledgments

The Authors gratefully acknowledge support in the framework of ESA High Power MPD Systems (Contract number 21797/08/NL/PA) and EU HiPER (Project FP7, contract number 218859) program. Adam Boxberger author thanks gratefully for funding by the German Aerospace Center and German Federal Ministry of Economics and Technology (Contract number 50-RS-1002). The Authors would also like to thank Matthias Lau for kindly presenting these results at 33rd International Electric Propulsion Conference in Washington, *D.C.*

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