

Integral Measurements of 100 kW Class Steady State Applied-Field Magnetoplasmdynamic Thruster SX3 and Perspectives of AF-MPD Technology

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Abstract: Steady-state applied-field magnetoplasmdynamic thrusters feature a combination of high exhaust velocities, high thrust density, and power scalability, making them relevant for interplanetary missions. However, achievable thrust efficiencies of steady-state AF-MPD thrusters are typically between 20 and 45 percent.^{1,2,6} Motivated by promising capabilities, a new 100 kW gas-fed steady-state AF-MPD SX3 thruster was developed at IRS in the frame work of ESA project. The water-cooled laboratory model SX3 is a 100 kW class thruster featuring separate electrode propellant gas injection and maximum applied magnetic field of 400 mT. Integral measurements were performed in a wide power range under variation of arc current, cathode and anode argon mass flow rate. Experimental results presented here, show an overview with discharge characteristics and performance of SX3 thruster up to 115 kW arc power level and thrust efficiency around 40 % and more. Preliminary conclusions on AF-MPD thrusters with strong applied magnetic field are presented, including the outcome from DFVLR and current IRS activities. Additionally an outlook of possible future activities is presented, conducting to a new type of an Applied-Field MagnetoPlasmaDynamic EXtended Hall Effect Thruster (AF-MPD-EXHET) thruster concept.

I. Introduction

STEADY state applied-field magnetoplasmdynamic thrusters (AF-MPDT) feature relatively high exhaust velocities, relatively high thrust densities and good power scaling.¹⁻⁹ Therefore, these thrusters are predestined for interplanetary mission scenarios at high power level of +100 kW. High power AF-MPDT concept allows a realization of more practical NEP space vehicle in a power range between some hundred kW and some MW.¹⁰ The use of alternative propellants (such as argon, ammonia, hydrogen etc.) offers ISRU (In-Situ Resources Utilization) advantages compared to xenon as propellant for a high power main propulsion system.^{1,5} Furthermore, with increasing power level and propellant consumption ISRU will allow significant propellant mass and potential costs savings especially in repetitive mission scenarios and under consideration of specific sustainable space infrastructure.

Correspondingly AF-MPD thrusters have an optimal mix of trade-offs for a potential complementation of sustainable high power NEP infrastructure in the future, including automatic cargo transport (to human outposts), manned missions to Mars,¹⁰ and mission scenarios to the moons of Jupiter and Saturn, such as Enceladus or Europa. Moreover, an application and development of high temperature super conducting coil systems has significant

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synergetic aspects for know-how transfer to more advanced electrodeless electric propulsion concepts with magnetic nozzle design. However, compared to other electric propulsion concepts the technical readiness level of applied-field MPD thrusters is relatively low. There are still a few major challenges, which need to be addressed and solved in the future.

The current focus of AF-MPDT research at IRS is the increase of thrust efficiency by characterization and optimization of operating parameters at high power levels, which was partially investigated in the past by DFVLR at lower arc powers.^{1,2,11-14} For this purpose, a 100 kW steady state AF-MPD SX3 laboratory model thruster, was developed at IRS and put into operation. The goal of this project is a proof of feasibility and an investigation of the high magnetic field regime at an arc power level between 50 and 100 kW. The intent of this paper is to present a current breakthrough, which includes an overview of integral measurements on 100 kW class steady state AF-MPD thruster, and further promising perspectives and improvements of AF-MPDT technology.

II. Experimental Setup

A. Testing Facility

The AF-MPDT experiments have been performed in MPD testing facility Tank 8 (IRS laboratory), which has been adapted for higher power operation in steady state regime close to 100 kW arc power at strong magnetic field of 400 mT. The thruster and thrust balance assembly are implemented in stainless steel water cooled vacuum chamber with dimension of $\varnothing 2 \times 5$ m. The inside surface of the vacuum chamber was coated with ceramics in plume downstream region in order to prevent arc interaction with vacuum chamber. The central vacuum facility can provide a total throughput of more than $250\,000\text{ m}^3\cdot\text{h}^{-1}$ at approximately 1 Pa tank pressure and vacuum with minimal achievable pressure of ~ 0.5 Pa at argon mass flow rate of ~ 100 mg/s. The high power DC facility can provide up to 6 MW and current up to 48 kA @ 125 V or up to 6 kV @ 1 kA. For presented experimental results the MPD testing facility was equipped with 2 separate current controlled circuits, which can be adjusted in the range of 2.5 and 1 kA (extendable to 1.5 kA) with up to 1 kV each for operation of an AF-MPD thruster. Additionally 3 DC voltage controlled circuits can be implemented with a range of max. 40 A and up to 460 V. For the cooling purpose high pressure pumps with closed water cycle of the central cooling facility can provide up to 20 bar high pressure cooling water distributed in 4 cooling circuits: anode, coil, thruster assembly, and setup parts, with theoretical cooling power of ~ 600 kW. The data acquisition system with measuring program has an average measuring frequency of 10 Hz. Monitoring of vacuum chamber's pressure is done by Pfeiffer PKR 251 wide range pressure gauge. Current measurements are performed by measuring drop voltage on predefined shunts on both circuits via galvanic isolation amplifier. Structural and water temperatures are monitored by PT100 resistance thermometers (Class A). The anode and cathode propellant distribution is provided by a two pairs of Bronkhorst F-201CV type flow controllers with up to 10 and $100\text{ mg}\cdot\text{s}^{-1}$ of argon. The integral measurements have been assisted with an active broad band antenna with the frequency range between 20 kHz and 300 MHz. The antenna was placed outside the vacuum chamber next to observation window and coaxially to the thruster's axis. The Signal of the antenna was measured with oscilloscope.

B. Thrust Balance

For the purpose of direct thrust measurements, the MPD test stand includes a parallelogram pendulum thrust balance, which is connected via fixed frame with the vacuum chamber's tank lid (see Fig.1). The current supply decoupling of balance assembly was realized with flexible wire stripes made out of copper filaments (75 mm^2 each). In the case of cooling water channels, the tubes (Polyamide, 12×1.5) were mounted and fixed in a half circle shape perpendicular to the thruster's axis in order to minimize spring like loads of the tubes. Thrust acquisition has been done with the S-shaped force sensor (KD40s) with a nominal measuring force of 5 N and base accuracy of ± 5 mN, which can be moved on a linear unit towards the balance allowing a desired preload force or decoupling from thrust balance completely. In order to characterize the measured force sensor signal a calibration unit is implemented with 3 masses representing a force of ca. 1 N each. For calibration the weights apply a force in the thrust direction via thin Dyneema[®] line and two pulleys.

The evaluation of thrust consists of combined data analysis, which includes force sensor calibration (before/after), acquisition of force difference between steady state operation and arc shut down, tare forces (short circuit) and setup specific influence. For evaluation of setup dependency the force sensor was separately calibrated in a vertical position with same calibration masses applied in order to cover the influences of pulleys etc. compared

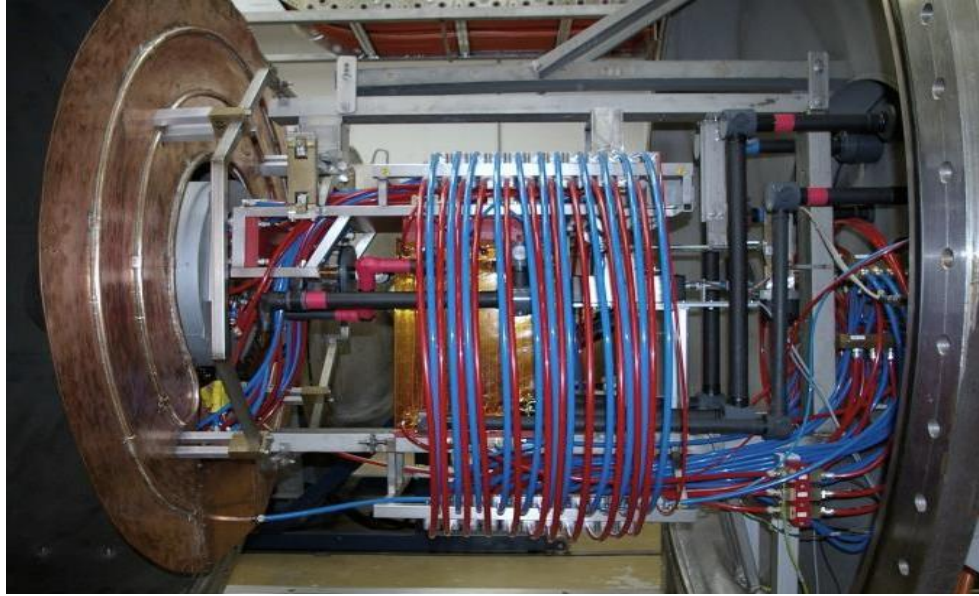


Figure 1. Implemented thrust balance and SX3 thruster inside of MPD testing facility (Tank 8).

to implemented condition. The short circuit calibration tare forces are measured with connected electrodes via modular coaxial electrode interlink and operating at specific current levels. Since normally the arc extends further plume downstream with higher magnetic fields,^{2,13} short interlink (25 mm) was used for tare forces measurements at 100 mT and long one (150 mm) at 400 mT, in order to replicate plasma plume conditions in a technical feasible way.

Overall the thrust can be measured with an accuracy of ca. ± 20 mN (without high pressure cooling water). With high pressure water cooling in operation the thrust measuring accuracy is about ± 350 mN, where the signal is oscillating around an average value in the amplitude range of ± 1 N. Due to relatively low effective thrust measurement accuracy the cold gas portion of thrust was not included in presented results. However, high pressure water supply causes an oscillation of force sensor signal making the thrust measurements overall difficult and less precise especially combined with thermal drifts.

C. 100 kW Class Steady State Laboratory Thruster SX3

The 100 kW steady-state AF-MPD thruster SX3 was designed as costs effective water cooled laboratory model (shown in Fig.2 and Fig.3). The anode assembly consists of two laser welded copper parts. The hollow cathode made out of thoriated tungsten rod was electron beam welded on copper adapter, which is connected via thread connection with cathode liner. All insulators in arc proximity (anode liner and cathode centering) are a made of boron nitride. Other insulation parts were realized with alumina, PEEK, and PVC. The thruster has a modular design

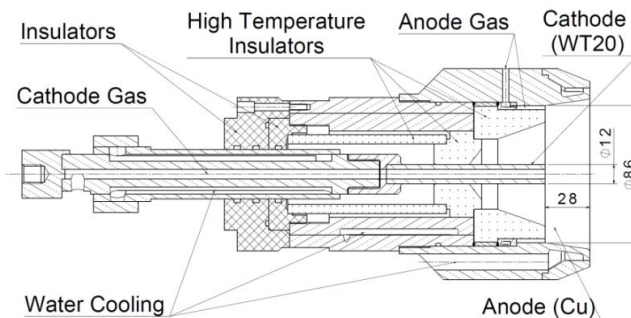


Figure 2. Schematic view of laboratory model SX3 with initial anode liner BN18.

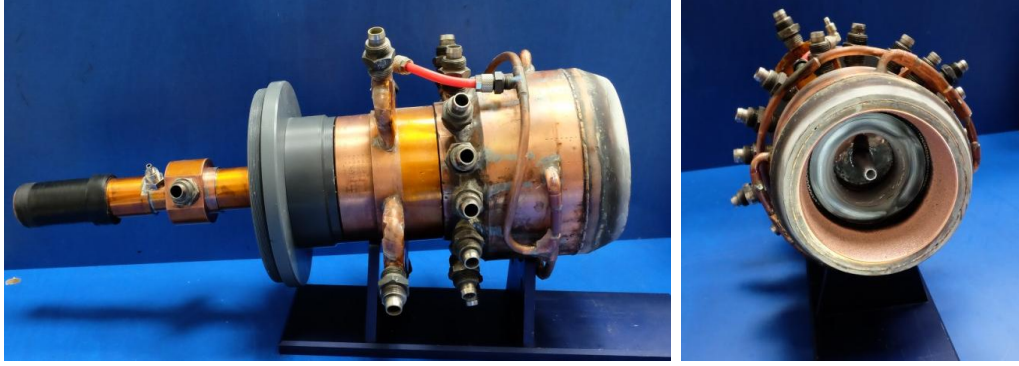


Figure 3. SX3 thruster after test campaign without SX coil (BN3).

allowing a potential implementation of different electrodes. Nevertheless, the more practical way to change the electrode ratio (anode/cathode) will be realized via new cathode rather than anode assembly. Current electrode ratio of 7.167 is relatively high compared to other applied-field MPD thrusters.⁴⁻⁹ A maximum implementable cathode outer diameter of - 24 mm and electrode ratio of - 3.583 respectively is considered for potential extension of experimental data towards high current regime. Before each implementation procedure into experimental setup the thruster assembly has been checked for potential gas and water leakages. An additional heat shield between applied-field coil and thruster protects cooling water and gas supply PA pipes. The BN anode liner had initial length of 18 mm and has been shortened during test campaign to 7 and finally to 3 mm length.

The assembly of applied magnetic field coil has dimensions of D500 / d325 mm and is 145 mm long. The coil turns are not equally distributed, but in a way, that the amount of turns is decreasing towards outer boundary. The total amount of coil turns is about 71, which are implemented via soft copper pipes (15 m, 10x1 mm). An implemented assembly of SX3 thruster and SX coil is shown in Fig.4. The characterization of the coil was performed with a Hall probe model 5180 from F.W. Bell (STD 18-0404 and SAD 18-1904) in air conditions with radial and axial probe separately at the same coil current conditions. A typical operative range of the coil is between 235 and 1880 A with the slope of 50 mT per 235 A. The coil allows a maximum applied magnetic field of 400 mT at electric power of ca. 285 kW. However, the power of applied-field coil is not included in the evaluation of thrust efficiency (thrust power/arc power). This is justified by consideration of usage of permanent magnet (at small power scale) or HTSC (high temperature superconductor) coil in high power application case (e.g. +500 kW). The required power for cryocoolers in a complex high power AF-MPDT system needs to be addressed in future activities with respect to thrust, arc power, and total system efficiency. However, from a standpoint of current second generation HTSC technologies, an AF-MPDT system seems to be feasible and promising e.g. for near term high power NEP applications.

III. Experimental Results

A. Characterization of Tare Forces

Tare forces have been characterized in vacuum conditions (~ 1 Pa) by implementation of specific interlink between electrodes (see Fig.4) and operation of the thruster in short circuit mode in the current range between 200 and 700 A. The results of tare forces characterization for 100 and 400 mT are shown in Fig.5 including measurements in series with increasing current step by step and single condition measurements. At 100 mT a tare forces have a clear negative trend, while in the case of 400 mT the measurements in series and as single currents differs from each other with a maximum force difference of 0.8 N. Following aspects might affect the measurement: magnetization of setup parts, sudden movement of current supply copper braids, and thermal drift due to PA tube heating of applied field coil. Considering given trends, these results are comparable with measurements from DFVLR on short circuit tare forces performed with X13 thruster.^{11,12} Nevertheless, a linear fit of the given data was used for further thrust data analysis presented in this paper. A deeper analysis and review on tare forces will be done in the coming test campaign.



Figure 4. Mounted SX3 thruster and SX coil assembly (left) and implemented electrode interlink (150 mm) for short circuit measurements (left).

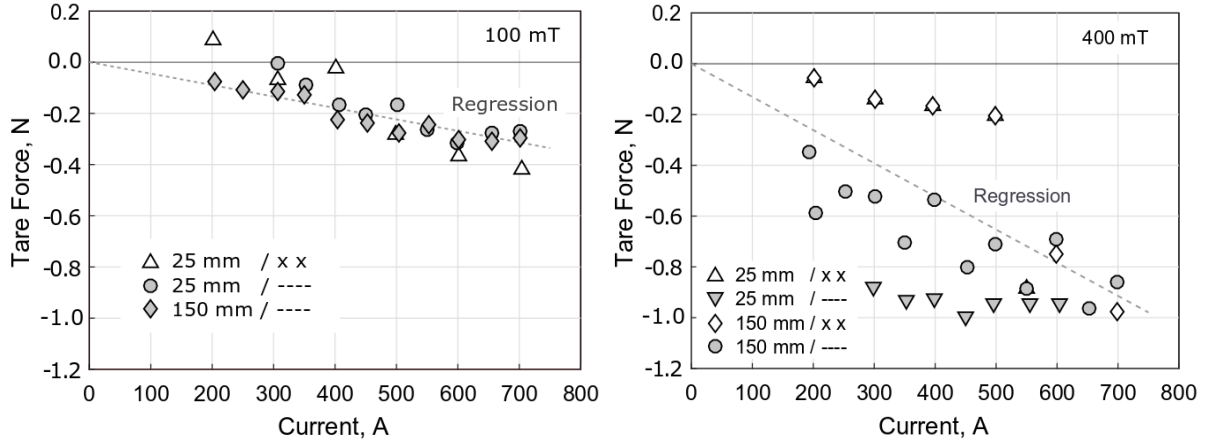


Figure 5. Tare forces for short circuit current range of 200 - 700 A at 100 (left) and 400 mT (right) respectively; (---) measurement in series, and (x x) separate measurement.

B. Variation of Mass Flow Rate Ratio

Since power supply is limiting factor on a deep space vehicle, a variation of operative parameters have been tested at constant arc power of ~ 50 and 100 kW and applied magnetic field of 400 mT. Therefore, the arc current has been adjusted accordingly. Figures 6-8 show the influence of mass flow rate ratio μ_A , which is defined as a ratio between anode and total mass flow rate, on thruster's performance.

$$\mu_A = \frac{\dot{m}_A}{\dot{m}_{pl.tot}}. \quad (1)$$

At ~ 50 kW arc power, the evaluated thrust values are between 0.72 and 1.43 N and correspond to a thrust to power ratio between 14 and 28 mN/kW. The specific impulse varies between 1315 and 4000 s and thrust efficiency between 9.97% (0.83 kJ/mg = $P_{arc}/\dot{m}_{pl.tot}$) and 46% (1.66 kJ/mg) respectively. The best performance has been achieved with lower anode gas fraction of 0.2 for all 3 total mass flow rates. Overall the high thrust efficiency is comparable with DLR's X16 thruster with a thrust efficiency of 38% at 11.6 kW arc power, 0.6 T and argon as propellant (21 mN/kW and 1.65 kJ/mg).²

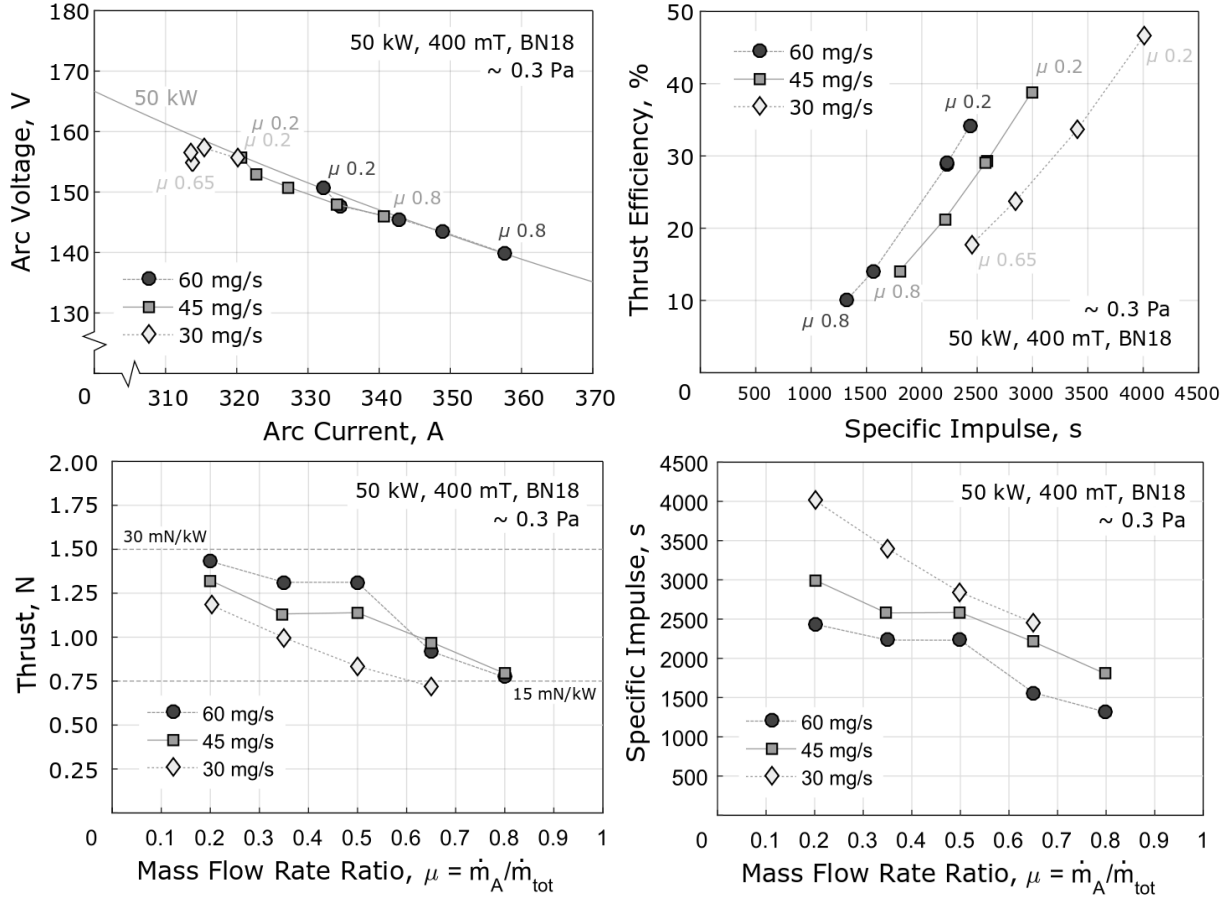


Figure 6. Influence of anode gas ratio μ_A (argon) at 50 kW arc power.

In contrary at 100 kW arc power and 120 mg/s of argon, the higher anode gas fraction of 0.8 produces better performance (Fig.8). However, these results are very close and are in the range of ~ 2450 s, ~ 35 % and ~ 2.85 N. The total mass flow rate is relatively high with respect to arc power (~ 0.83 kJ/mg) and is equal to 50 kW operation at 60 mg/s (~ 0.83 kJ/mg, Fig.7). The DFVLR's X13 results from 1970ties show that, arc voltage and thrust increase with lower anode gas fraction (at constant mass flow rate, arc current and B-field).¹¹ Also at constant B-field and constant mass flow rate, but relatively low arc current the thrust efficiency is higher for low anode gas fraction.¹² This behavior however, changes with relatively higher arc current towards better thrust efficiency with higher anode gas ratio (arc current, B-field and mass flow rate are constant).¹² By taking DFVLR results into account, equal trends with IRS SX3 thruster (Fig.6 and Fig.8) can be identified. However, the results from DFVLR have been produced not at constant arc power. This makes a qualitative comparison between different mass flow rate ratios a difficult task, since at same current level, the arc voltage varies and so the arc power, partially with a difference of up to 25 %. In variation of arc current in 120 mg/s data (Fig.7) an unpredicted behavior of thrust in the range of 350-500 A has been observed especially with anode mass flow rate above 55 mg/s (e.g. 60+60, 42+78 and 24+96), leading to relatively high thrust values and thrust/power ratio more average value of 30 mN/kW. This trend is more dominant at higher anode gas and is relatively soft at 60 mg/s (Fig.7). One of possible aspects might be the oversaturation of anode region with neutrals, leading to higher thermal portion of thrust. However, error sources such as thermal offset drift, magnetization etc. can't be excluded. Nevertheless, beyond 80 kW (see Fig.7) arc power the performance converges at ~ 30 mN/kW especially towards 100 kW (Fig.8).

Overall the presented results of mass flow rate ratio impact show the significance of distribution and optimal utilization of propellant inside of arc discharge volume for efficient operation of an AF-MPD thruster. Furthermore, an operation with low anode gas fraction is more prone for ambient re-entrainment effect than at higher anode gas fraction, leading to potential higher influence of the arc voltage and thrust efficiency.

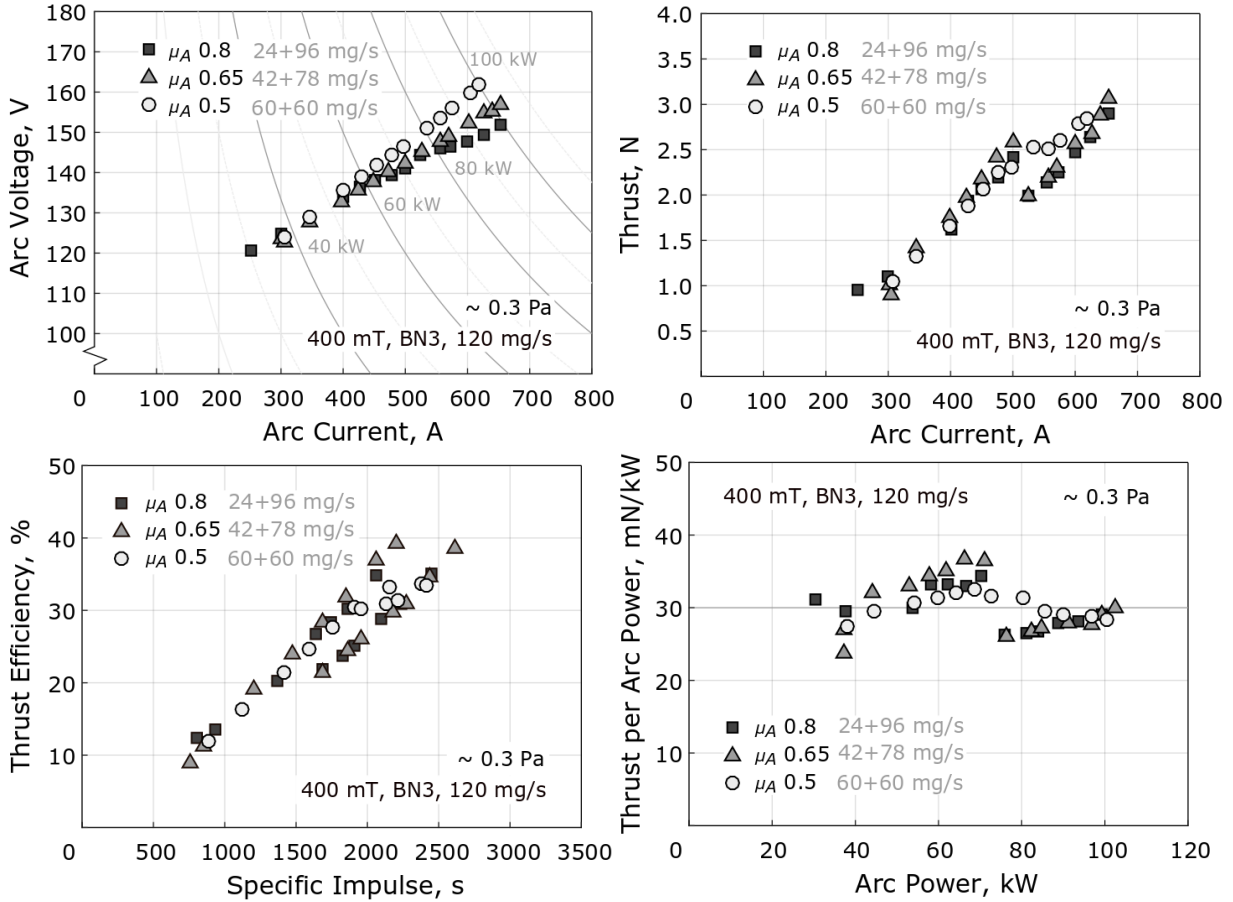


Figure 7. Influence of anode gas ratio μ_A (argon) at arc power up to ~100 kW.

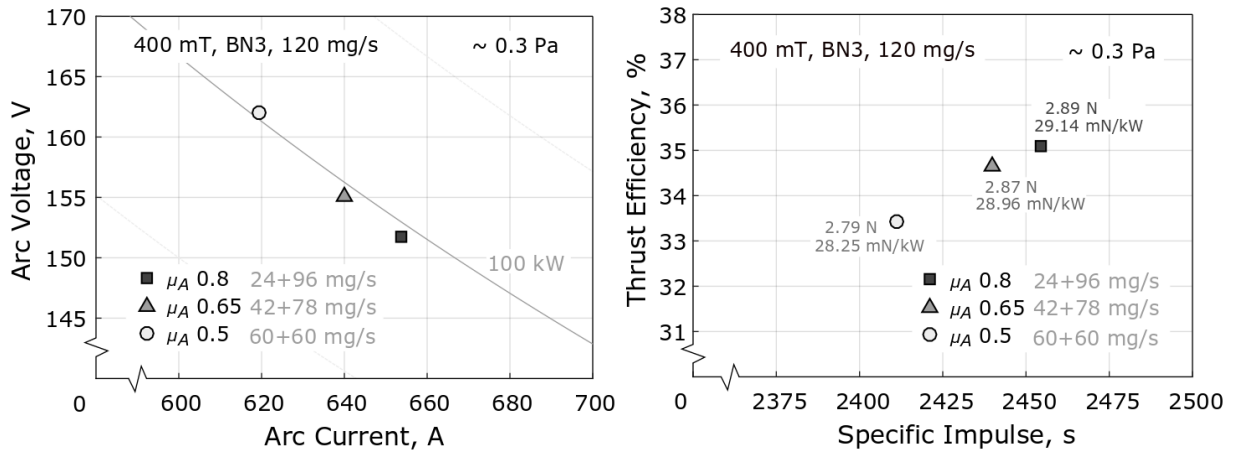


Figure 8. Influence of anode gas ratio μ_A (argon) at arc power of ~100 kW (part of Fig.8).

C. Variation of Total Mass Flow Rate

Since the initial goal for SX3 thruster was a steady state operation at 100 kW arc power, the anode liner has been shortened to 3 mm in order to allow higher arc currents. With BN3 liner and increased anode inner surface area for rotating arc spoke, the current levels were increased up to 750 A and so arc power up to 100 kW and more. The shorter BN liner and bigger exposed anode inner surface leads automatically to a different distribution of neutral species in discharge volume especially in the proximity of the anode and discharge volume in general.

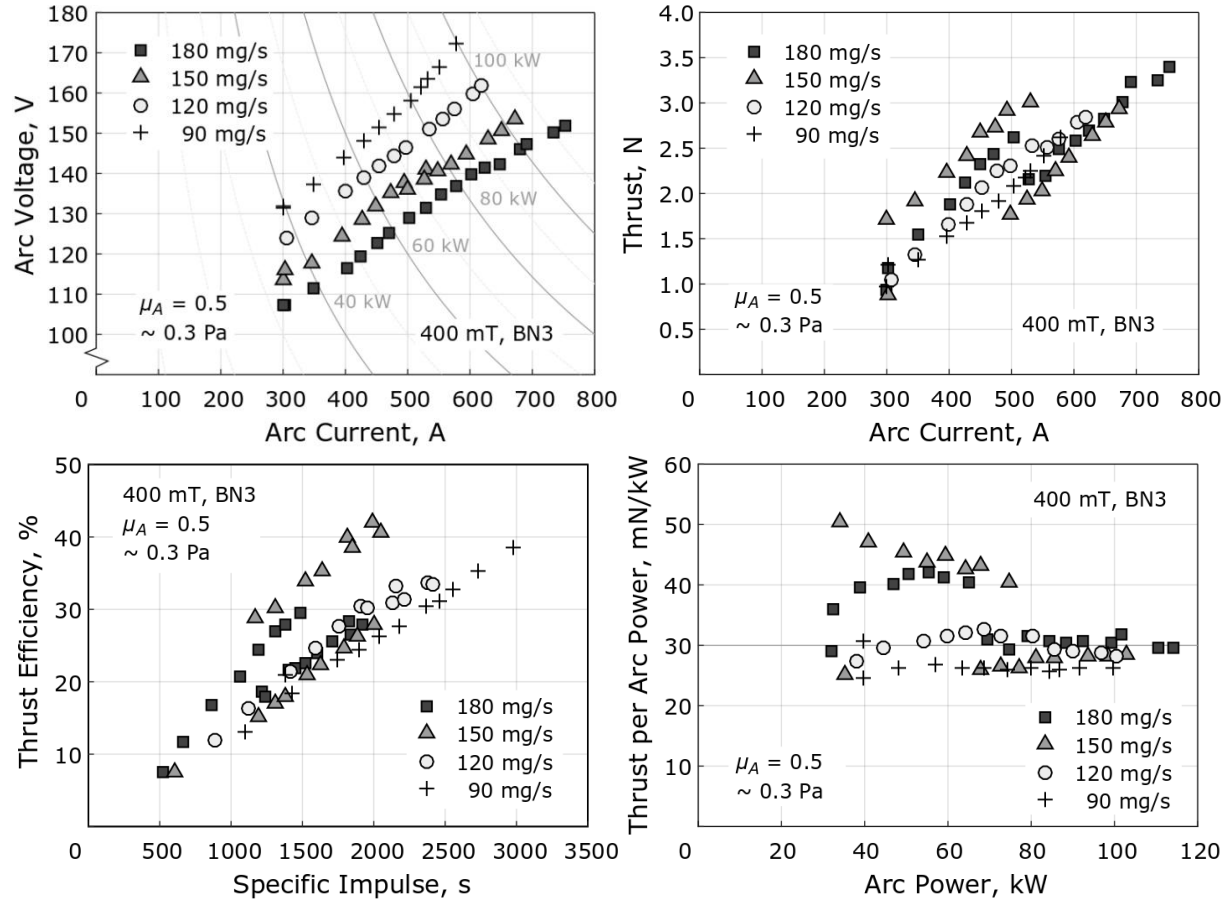


Figure 9. Influence of total mass flow rate with anode ratio of 0.5 for arc power levels up to 114 kW.

Figure 9 shows the results of variation of total argon mass flow rate up to 180 mg/s and anode gas ratio of 0.5. As expected lower total mass flow rates show a better utilization of propellant and higher thrust efficiency with exception of data in the range between 300-500 A (40-50 mN/kW) at high anode mass flow rates above 60 mg/s, as in the case previous data in Fig.7. Considering data in the range of ~ 30 mN/kW, the highest thrust efficiency of ca. 38 % has been achieved at 45+45 mg/s (99.6 kW, 2.62 N, 2970 s, 26.36 mN/kW, 1.1 kJ/mg). The highest thrust of 3.39 N and evaluated specific impulse of ~ 1916 s has been achieved with mass flow rate of 180 mg/s (90+90 mg/s) at ca. 114.36 kW with thrust efficiency of ca. 27.8 % (29.6 mN/kW, 0.635 kJ/mg).

For preliminary conclusion it can be assumed that, in order to achieve higher thrust efficiency at given geometry and applied magnetic field, the SX3 thruster needs to be operated at lower mass flow rates, optimal propellant distribution and close but not in the region of onset phenomenon.

D. Performance

By lowering total mass flow rate and increasing arc power to mass specific power of 1.66 kJ/mg (e.g. 12+48 mg/s and 100kW), an increase in specific impulse and thrust efficiency has been expected. Figure 11 shows the discharge and performance of experiment with argon mass flow rate of 12+48 mg/s (cathode+anode). The plume appearance is shown in Fig. 15. Initially the discharge characteristic of the arc increased linearly, where propellant was better utilized towards 430 A. By surpassing ~ 440 A, the arc voltage (~ 150 -225V) and plume became instable with high frequency fluctuations. This region of operation is often referred as onset phenomenon,⁶ where the arc voltage drastically increases, whereas thrust efficiency drops. Furthermore, due to limited acquisition frequency, the evaluated arc voltage and arc power above 440 A are highly unlikely sufficiently resolved in time, and therefore the effective arc voltage might deviate by up to 25 %. However, the plume fluctuations and high oscillations of the arc voltage indicate starvation of the rotating arc spoke. In stable operation regime the maximum arc power have been

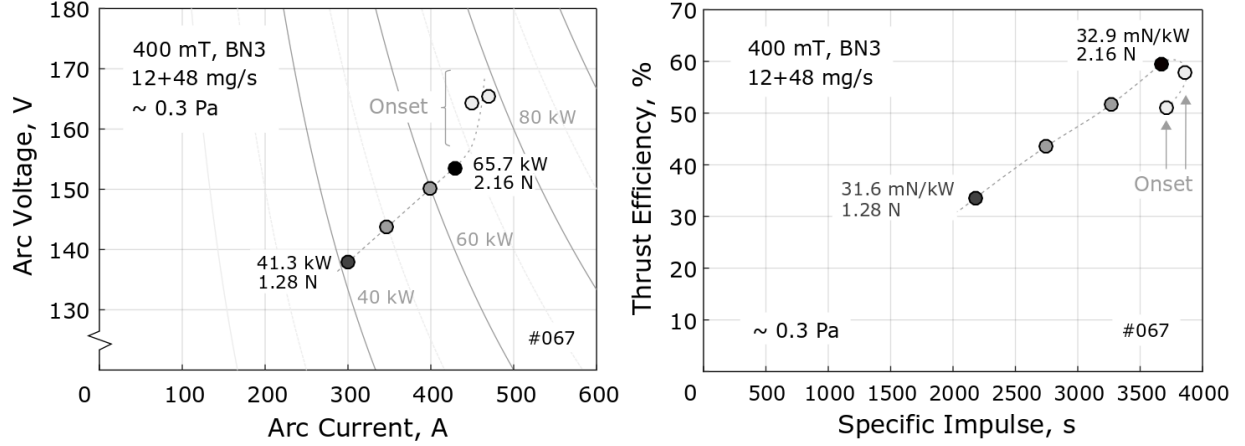


Figure 10. Performance with anode gas ratio of 0.8 at high power up to “onset” condition (#067).

achieved at 65.7 kW with an arc current of 428 A and arc voltage of 153.3 V. The evaluated thrust is about 2.167 N, which corresponds to specific impulse of 3670 s and thrust efficiency of about 59 % (1.083 kJ/mg, 32.9 mN/kW).

Table 1 shows an overview of power balance of calculated arc power $P_{arc,calc.}$, which is evaluated via Eq. (2) and Eq.(3). Therefore, the thrust power $P_{thr.}$ has been evaluated via measured thrust and mass flow rate. The heat power from anode $\dot{Q}_{an.}$ and anode liner $\dot{Q}_{an.l.}$ have been estimated with measured temperature change (± 0.3 K) between reference (after arc shut down) and operation at given arc current, whereas cooling water mass flow rates have been measured after experiment in the air conditions at specific channels without any heat load (± 2 kg/h). For estimation of frozen flow losses $\dot{Q}_{fr.}$ a single ionization of argon propellant has been assumed. In case of cathode losses $P_{cath.}$ a cathode voltage of 2 V has been used.

The results of power balance are visualized in Figure 12. The lowest deviation of ca. 2 % from measured arc power is at 428 A close to reference temperature after the shutdown of the arc. In contrary the high deviation of ca. 30 % at lower arc currents is likely caused by thermal drift of inlet temperature of cooling water. Table 2 shows a comparison between measured and calculated thrust power, thrust and specific impulse (Eq.(4)). The highest deviation of ca. 40 % between calculated and measured thrust is as expected at initial conditions and lower arc current of 300 A (equivalent to calc. arc power). The data above 440 A (begin of onset) is in special case, since the arc voltage acquisition was not sufficiently resolved in time. Overall the power balance shows that measured thrust levels are qualitatively in the range of estimated values, especially close to reference temperature.

$$P_{arc,calc.} = P_{thr.} + \dot{Q}_{an.} + \dot{Q}_{an.l.} + \dot{Q}_{fr.} + P_{cath.}, \quad (2)$$

$$P_{arc,calc.} = \left(\frac{1}{2} \frac{T_{thr.}^2}{\dot{m}_{tot}} \right) + (\dot{m}_{w,an.} c_{p,w} \Delta T_{w,an.}) + (\dot{m}_{w,an.l.} c_{p,w} \Delta T_{w,an.l.}) + \dots \quad (3)$$

$$\dots + \left(\frac{\dot{m}_{tot} N_A E_{Ar,i}}{M_{Ar}} \right) + (U_{cath.} I_{arc}),$$

$$P_{thr.,calc.} = \left(\frac{1}{2} \frac{T_{thr.,calc.}^2}{\dot{m}_{tot}} \right) = P_{arc} + \dot{Q}_{an.} + \dot{Q}_{an.l.} + \dot{Q}_{fr.} + P_{cath.}. \quad (4)$$

The presented breakthrough results (Fig.10) show further promising improvements in operation of applied-field MPD thrusters at high magnetic fields. Moreover, it leads to a preliminary conclusion that for 100 kW arc power and maximum thrust efficiency for a given geometry (SX3) a higher mass flow rate will be required (e.g. 12+60 mg/s and 1.22 kJ/mg @ 100 kW). Figure 12 shows the total operational envelope of 2016 test campaign.

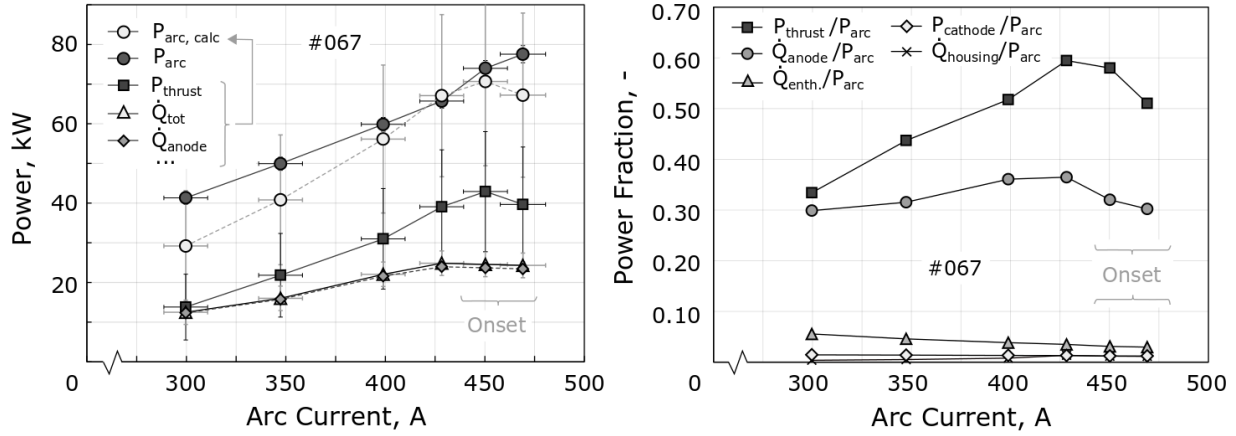


Figure 11. Power balance and power fraction (#067: 400 mT, 12+48 mg/s, Ar, ~0.3 Pa, BN3).

Table 1. Power balance from energy conservation assuming frozen losses and cathode power (#067: 400 mT, 12+48 mg/s, Ar, ~0.3 Pa, BN3, *indicates conditions with start of onset).

I_{arc} A	P_{arc} kW	$P_{thr.}$ kW	$\dot{Q}_{an.}$ kW	$\dot{Q}_{an.l.}$ kW	$\dot{Q}_{fr.}$ kW	$P_{cath.}$ kW	$P_{arc,calc.}$ kW	Dev. P_{arc} %
exp. data or calculated from exp. data					via assumption		calculated data	
300	41.32	13.80	12.35	0.16	2.30	0.60	29.20	29.3
347	49.94	21.82	15.75	0.25	2.30	0.69	40.82	18.3
399	59.86	30.99	21.59	0.48	2.30	0.80	56.16	6.2
428	65.72	39.07	23.97	0.89	2.30	0.86	67.09	2.1
450*	74.00*	42.91	23.68	0.87	2.30	0.90	70.66	4.5
469*	77.75*	39.67	23.42	0.89	2.30	0.94	67.21	13.6

Table 2. Calculated performance from arc power and portions from power balance in Table 1 (#067: 400 mT, 12+48 mg/s, Ar, ~0.3 Pa, BN3, *indicates conditions with start of onset).

I_{arc} A	$T_{thr.}$ N	I_{sp} s	$P_{thr.}$ kW	$\eta_{thr.}$ %	$P_{thr.,calc.}$ kW	$T_{thr.,calc.}$ N	$I_{sp,calc.}$ s	Dev. $T_{thr.}$ %
exp. data or calculated from exp. data					calculated data from losses (Table 1)			
300	1.288	2185	13.80	33.4	26.52	1.785	3029	38.6
347	1.619	2748	21.82	43.7	31.65	1.950	3309	20.4
399	1.930	3275	30.99	51.8	35.49	2.065	3504	7.0
428	2.167	3677	39.07	59.5	38.56	2.152	3653	0.7
450*	2.270*	3853	42.91	58.0	47.14	2.380	4039	4.8
469*	2.183*	3705	39.67	51.0	50.93	2.474	4198	13.3

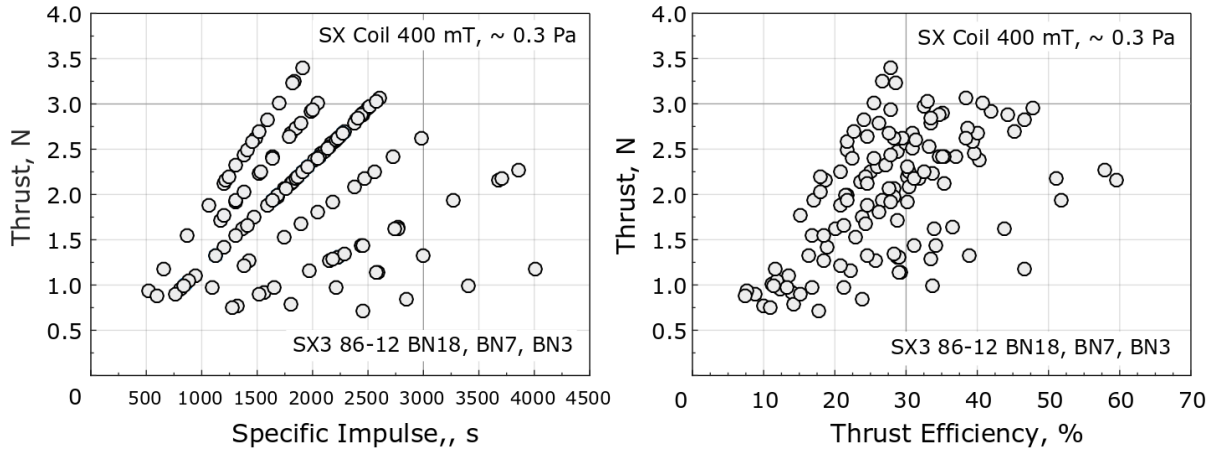


Figure 12. Performance envelope of SX3 thruster at 400 mT from 2016 testing campaign.

E. Broad Band Active Antenna

An active broad band antenna with a frequency range between 20 and 300 MHz has been used for the whole test campaign. The antenna was placed coaxially to the thruster (~ 1.4 m) outside of the vacuum chamber and in direct proximity of view port (acrylic and quartz). 3 separate sequential signals per condition have been acquired. The measured oscilloscope data was post processed via FFTW in Matlab code and analyzed for frequency spectrum.

Due to the presence of arc, most relative amplitude changes have been observed in kHz range. By considering investigations from Loveberg, Larson, Krülle et al.,¹⁴⁻¹⁶ the measured frequencies between 20 and 60 kHz in SX3 thruster indicate a presence of a rotating arc spoke. However, additional analysis of the data will be required. Moreover, experiments with high speed camera are in consideration in order to extend presented activities.

F. Plume

By comparing plume appearance at relatively low and high mass flow rates and applied magnetic fields of 100 and 400 mT, a clear visual difference can be observed (Fig.13-15). The bulging of anode and especially of cathode jet (plume downstream) at high magnetic field of 400 mT in Fig.14 is clearly visible compared at equal current level, mass flow rate, but lower magnetic field of 100 mT and arc voltage respectively (Fig.13). This indicates also bulging of the arc current with increasing B-field as was shown by DFVLR with X9 thruster,¹³ and is comparable to the plume of X16 thruster.²

Additionally, the anode plasma column is brighter at high magnetic field. Moreover, the pink glow around the plume increases with applied magnetic field (shown in Fig.15), especially at lower mass flow rates below 60 mg/s (e.g. 50 kW conditions and anode ratio of 0.2). This might be related to higher re-entrainment effect or interaction of the arc with ambient.

G. Cathode Erosion

The SX3 thruster has been operated in 2016 for more than 13 hours in total. Over 100 ignitions have been performed. Due to amount of ignitions with cold cathode, a higher erosion rate can't be excluded. Figure 16 shows the single channel hollow cathode before and after experimental test campaign performed in 2016.

The erosion of cathode material is not only visible on the cathode's tip, but also on the outer surface. It can be assumed that after several ignition processes the curvature of original design (Fig. 16 left) were leveled out by the natural round curvature, due to electric field peaks.

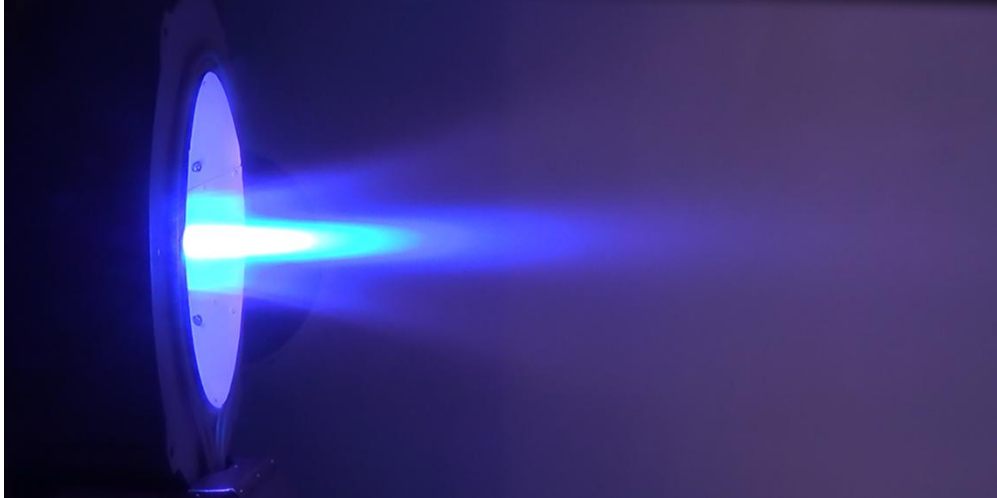


Figure 13. Visual plume appearance at 100mT, 62 kW, 700 A, 60+60 mg/s argon (BN 18).

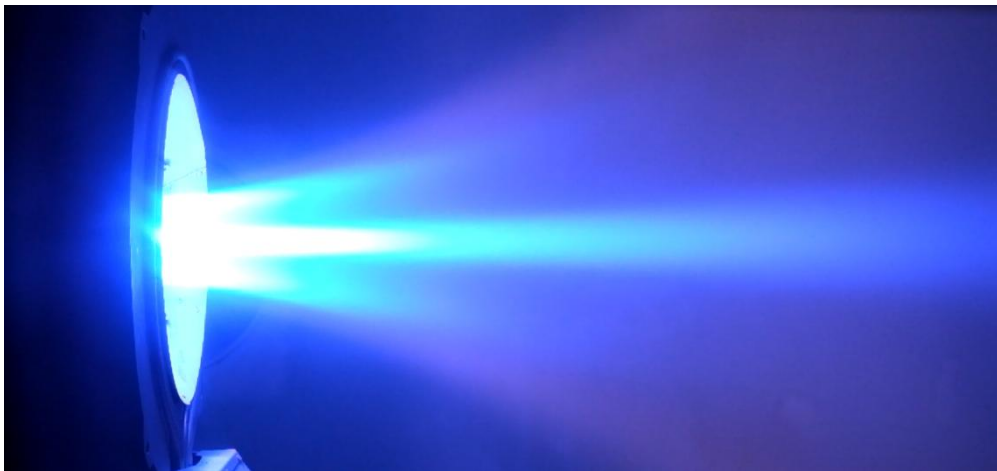


Figure 14. Visual plume appearance at 400mT, 115 kW, 690 A, 60+60 mg/s argon (BN 3).



**Figure 15. Visual plume appearance at 400 mT, 65.7 kW, 428 A, 12+48 mg/s argon (BN 3),
(#067: 2.16 N, 3670 s, 56 %, 32.9 mN/kW, 1.083 kJ/mg).**

Additionally, under assumption of the arc attachment on the cathode's tip at high magnetic field, the given cathode is undersized for tested currents especially above 400 A. That means at 400 mT and high arc currents up to 700 A, the cathode temperature and erosion rate are likely very high, which leads to conical shape with maximized surface for respective required thermionic electron emission. Furthermore, due to the water cooling on the cathode flange and repetitive ignitions without preheating, a crack appeared along the cathode surface (see Fig.16), mostly due to the solid and relatively thick cathode design. However, the given erosion and crack of the cathode had no sign of impact on operation of the thruster (ignition, stability etc.).

Nevertheless, the design of single channel cathode proves to be robust for a high power steady state applied-field MPD thruster and can be improved by using of secondary bulk electron emitter such as LaB_6 , which is also considered by other groups in recent research.^{17,18}

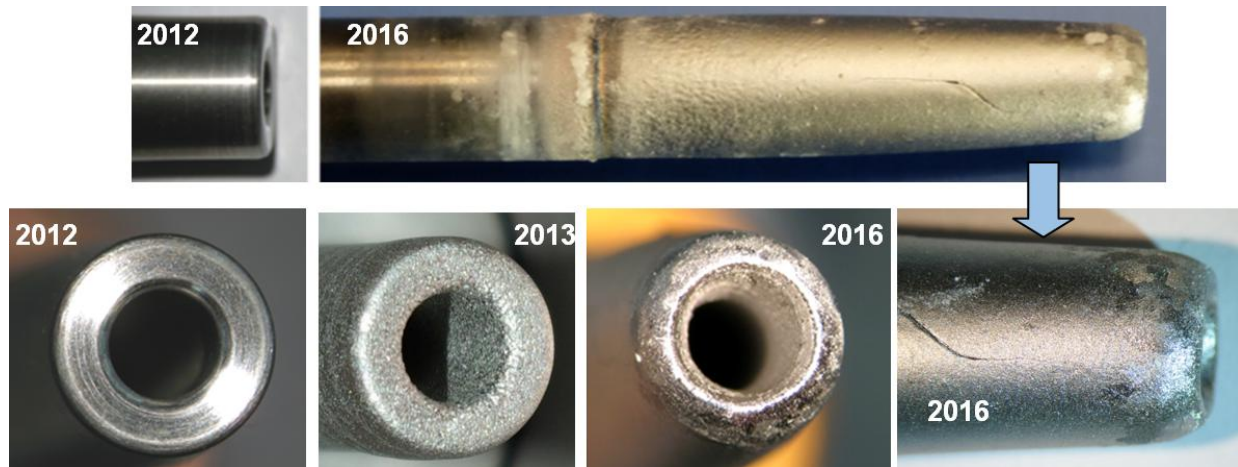


Figure 16. WT20 Hollow cathode initially in 2012 (left side), after experiments with SX coil in 2013, and after test campaign in 2016 with a total runtime of ~ 13 h (right side).

H. Impact of Testing Facility

The presented results in this paper are very promising. However, the re-entrainment effect has still potential influence on arc voltage and thrust at given pressure of ~ 0.3 Pa, which is one order above of recommended pressure of 0.05 Pa.^{2,6} Additionally, the effect of ambient is supported by indicated pressure drop (during operation, plume upstream), which disappears after shut down of the arc. This effect is absent during tare forces measurements at equivalent current levels (short circuit) and ambient pressure of ca. 1 Pa, which means a potential re-entrainment of ambient still takes place. Especially on most efficient conditions the influence of ambient pressure on arc voltage and performance might play a significant role. Further experiments with higher ambient pressure and its influence are in preparation and will be presented in near future.

High oscillations of the force sensor signal caused by the high pressure water supply decrease the overall accuracy of thrust measurement. An implementation of pressure dampers and laminar flow filters for high pressure cooling water could potentially improve the accuracy of measurement and are considered for next testing campaign in 2017. Thermal drift of cooling water tube temperature might lead to offset drift, which especially important for thrust values at low arc current (initial operation) compared to high values (before shutdown), since the shutdown procedure leads to well defined change of measured force. A magnetization of setup parts might also be critical and was reported by DLR during X13 experiments.¹²

Deeper improvements of the thrust balance and measuring procedures will be required and are in consideration for next test campaign, which will also include a review of most promising conditions presented in this paper. This means the presented results are potentially subject to potential change.

IV. Future Perspectives of AF-MPDT Technologies

Since 1960ties several different AF-MPD thrusters have been developed and tested.⁶ Two major steady-state AF-MPDT design trends tend to stand out through their operational regimes and electrode design and propellant distribution:

- High current operation in relatively weak applied magnetic field (~ 0.1 T),^{5-9,19}
- Comparably lower current operation in strong applied magnetic field ($+ 0.4$ T).^{1,2,12,13,19}

Also some devices have been operated in between. Additionally there is a sub group of MPD arcjet thrusters with nozzle like anode, small electrode ratio and operated in moderate applied magnetic fields around 0.2 T (mainly developed and tested in Japan).^{4,20-23} However, the outlined differentiation is more important in a sense of further divergent potential optimization of acceleration mechanisms rather than performance comparison, since all research trends have their merits for extrapolation and understanding purpose of MPD based thrusters.

A. Conclusions on MPD Thrusters with Strong Applied Magnetic Field

Steady-state AF-MPD thrusters with strong applied magnetic field have been intensively developed and tested at DFVLR (today DLR) between 1966 and 1974.^{1,2,11-14} Several thrusters have been built and tested, where each new thruster was a follow up development of the precursor. The applied magnetic field has been gradually increased from 0.2 T (X9) to 0.36 T (X13), and finally to 0.6 T (X12 and X16 thruster). However, the increment of thrust efficiency has been achieved not only by operation in strong magnetic field, but also by separate propellant injection in the electrode region.^{11,12} The points below give a an overview and author's interpretation of DFVLR MPD development and research outcome, which mostly given in Ref.2.

- Similar to other groups; an increase of applied magnetic field can increase the thrust efficiency especially at relatively low arc power, where self-induced magnetic field plays a minor role (X9, X12).^{1,2}
- With the X12 thruster high arc voltage up to 200 V have been reached at strong magnetic field 0.5-0.6 T. Up to 80 % of power was contributed via anode losses, indicating arc starvation and insufficient heavy particles in the anode region.¹¹ This led likely to development of a thruster with separate gas injection, mainly to reduce anode losses (X13).^{2,11,12} According to Ref.2, X13 was designed for investigation of impact by mass flow rate distribution in discharge volume.
- Tested with X13 thruster, high cathode fraction has significant impact on thrust (above critical mass flow rate: small influence on arc voltage). Whereas high anode gas fraction can drastically decrease arc voltage (below saturation level: smaller impact on thrust) (X13).^{2,11} The balance between anode and cathode gas fraction is reflected in thrust efficiency variation. From the X13 outcome, high cathode gas fraction preferable at low magnetic field and relatively low arc currents, whereas high anode gas fraction leads to higher thrust efficiency at strong magnetic field and high arc current.¹²
- The final DFVLR design philosophy contains optimized strong and slender applied magnetic field, substantial anode gas fraction for decrease of anode losses and better current transport and to damp instabilities, high degree of ionization, hot anode for better conductivity and improved current transfer.² The consequence is reflected in X16 thruster design, with 38 % thrust efficiency at 0.6 T and only 11.6 kW of arc power and argon as propellant (see Fig.17).^{1,19}
- Operation at lowest pressure as possible, since even below 0.1 Pa an interaction of plume with ambient and influence on performance has been observed (X16).²

The outlined bullets were fundamental for establishment of current development and research of AF-MPD thrusters at IRS. In 2005 on a basis of X16 a passively cooled thruster AF-MPD ZT1 has been designed and put successful in operation in 2011.²⁶ However, during ignition at stronger magnetic field the thruster was irreparably damaged, due to inner discharge.

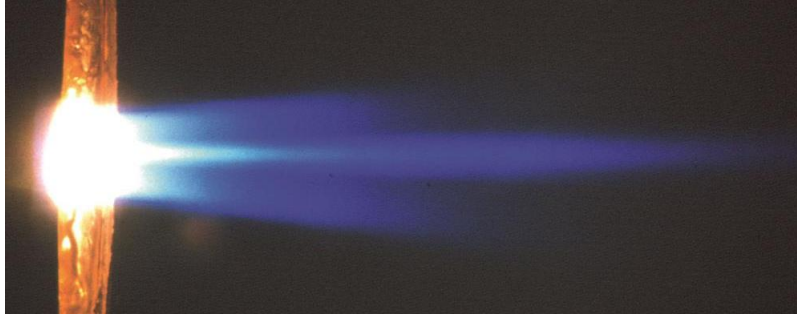


Figure 17. Plume of DFVLR X13 thruster in steady state operation at 600 mT (provided by Gerd Krülle).

In 2012 a new 100 kW class laboratory AF-MPD thruster (SX3) was designed in the framework of ESA TRP project. Initial experiments have been performed with modified applied field coil from ZT1 thruster. The following list gives an overview of achieved milestones of SX3 thruster in steady state operation with argon.

- SX3 experiments with small ZT coil demonstrated the importance of optimized B-field topology. Furthermore, the plume was very poor leading to secondary discharges, plume fluctuations and high plume divergence. The design of new coil with slender field topology and low gradient of the B-field over thruster's axis drastically improved plume stability and confinement in typical lance shape (equal to X16 and ZT1, see also Fig.17).^{2,19,26} The consequence of this design is an increased acceleration volume, extended arc and higher arc voltage and lower arc current required for specific arc power. Furthermore, due to high extension of the arc, the plume confinement can be only maintained with insulated vacuum chamber (leading to higher arc voltage).²⁸
- Operation of SX3 thruster in steady state, with argon as propellant at 400 mT and high arc power up to 115 kW, has shown the feasibility of scalability of the X16 design, leading to prove of concept, with appropriate confined plume, stable and efficient operation. At constant mass flow rate (60+60 mg/s) and equal arc current (~ 700 A) the arc voltage increases from 100 mT and 88 V up to 166 V at 400 mT.
- Mass flow rate ratio trends with respect to thrust, thrust efficiency and arc voltage correspond to X13 DFVLR data.^{11,12} Moreover, the variation of mass flow ratio at constant arc power (rather than arc current) shows a more transparent and qualitative comparison and provides a faster method for further optimization via distribution of neutrals in a given geometry.
- By gradually approaching towards onset regime the voltage oscillations start to increase in an expected almost exponential way, and the thrust efficiency reflects this in a sudden decrease (see exp.#067 Fig.10). High visual fluctuations in begin of onset (exp. #067) and broad band active antenna measurements with oscillations in 20-60 kHz range indicate a rotating arc spoke, since identified frequencies are in a comparable range as in segmented anode thrusters, tested by Maisenhlder and Larson.^{14,15} Furthermore, a long version of anode BN liner was ablated by approaching higher arc currents at constant mass flow rate, leading to potentially less diffuse rotating arc spoke.

The conclusions from DFVLR and recent IRS activity results show further potential of improvement in the range of 400 mT via operational parameters. An additional consideration of applied magnetic field increase up to 1 T could potentially increase the thrust efficiency (thrust power / arc power), e.g. by application of 2nd generation high temperature super conducting materials ($+1000$ A/cm).³² In case of SX3 thruster and under consideration of voltage increment ($U_{arc} = B_{AF,0} 260 \text{ V/T} + 62 \text{ V}$, for 60+60 mg/s and ~ 700 A) and same field topology, the thruster could operate at 1 T in the range of ~ 320 V for arc voltage, requiring for 100 kW only ~ 310 A. With proposed applied magnetic field of ~ 1 T, the arc would further extend in downstream direction. This might increase propagation of instabilities and lead to high voltage oscillations, since the arc voltage is the consequence of electric conductivity, which is highly dependent on distribution of species and the hall parameter.

Furthermore, the extension of the arc might increase a potentially higher dependency on the ambient particles, making experimental investigation of such devices in ground testing facilities a very difficult task. Especially at high arc powers and appropriate applied magnetic field the requirements for vacuum recipient size and vacuum pumps for required mass flow rates would drastically increase. Therefore, a technology demonstrator with a power range below 5-10 kW (< 25 kW) would be a most feasible solution regarding vacuum, power and thrust balance requirements, but also opens the opportunity for a potential flight experiment.^{19,24,25} An AF-MPD thruster in proposed power class at strong magnetic field could operate at arc currents below ~ 30 A, which automatically leads to a thruster concept in the next section.

B. AF-MPD-EXHET Concept

Applied-Field Magneto-Plasma-Dynamic EXtended Hall-Effect Thruster (AF-MPD-EXHET) concept is the consequence of continuous increase tendency of applied magnetic field, anode gas fraction, and high voltage operation regime. The AF-MPD-EXHET concept, shown in Fig.18, includes HTSC applied field coil, voltage controlled discharge, specifically designed keeper and hollow cathode with boride emitter (e.g. LaB_6), and emitter heater (not shown in Fig.18).

A similar design was tested by Kasuga et al. with LaB_6 hollow cathode without anode gas injection.¹⁸ The absence of anode propellant injection leads to concentration of species mainly in the cathode jet in the region of Hall current, so that an additional anode gas might further improve the operation of the thruster. Nevertheless, the LaB_6 HC AF-MPD thruster from the Ref. 18 shows the feasibility of such type of thruster. Furthermore, the thrust and thrust efficiency increase with stronger applied magnetic field and higher discharge current. The achieved thrust efficiency of the LaB_6 HC AF-MPD thruster is in the range of 25 % at 265 mT.¹⁸

The main working principle of AF-MPD EXHET, is that in the region of cathode jet the induced Hall current is constrained and propagates plume downstream towards lower magnetic field. The electrons, which are contributing to discharge current, return to the anode (through the anode jet) and produce ions via electron impact ionization of the neutrals species. Due to the charge separation, the ions around anode are accelerated via electric field. So the major acceleration of plasma is achieved by $\mathbf{E} \times \mathbf{B}$ (Hall current and swirl).

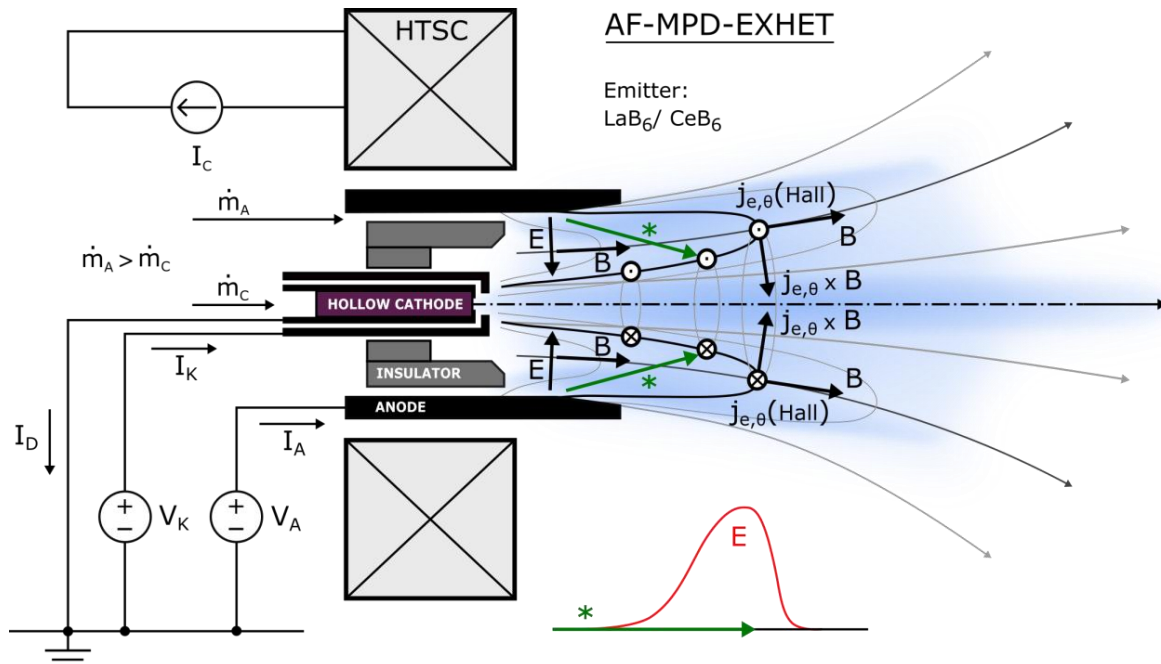


Figure 18. Schematic principle of AF-MPD-Extended Hall Effect Thruster.

Since the Hall component of thrust directly corresponds to increase of magnetic and electric field, a simplified formulation of thrust can be formulated equal to Hall effect thrusters²⁹ via Eq.(5),

$$\mathbf{T} = \iiint_V \mathbf{J}_{Hall} \times \mathbf{B} dV \quad (5)$$

with induced Hall current $\mathbf{J}_{Hall}$ due to $\mathbf{v}_e = \mathbf{E} \times \mathbf{B} / B^2$ drift and leading to

$$\mathbf{J}_{Hall} = -en_e \frac{\mathbf{E} \times \mathbf{B}}{B^2}. \quad (6)$$

From simplified perspective and neglecting of theta components of fields (E_θ , B_θ), in cylindrical coordinates the thrust can be expressed as

$$\mathbf{T} = en_e \begin{pmatrix} -\frac{B_z(E_r B_z + E_z B_r)}{B_r^2 + B_z^2} \\ 0 \\ \frac{B_r(E_r B_z + E_z B_r)}{B_r^2 + B_z^2} \end{pmatrix}, \quad (7)$$

which indicates acceleration caused by Hall current in axial and radial direction towards the z-axis. This implies a good plume confinement and relatively low plume divergence compared to current AF-MPDT design (e.g. X16, SX3). However, the acceleration process in realistic case is very complex, where Hall component of thrust and swirl are coupled.

In contrary to current controlled DC arc operation, the introduced concept combination (Fig.18) allows a manipulation of discharge region via applied magnetic and electric field. High voltage would potentially lead to a better plume confinement and less extension of the effective discharge region. Since voltage is not consequence of electric conductivity in this case, and low gradient of B-field along the thruster's axis is potentially not required, leading to a more compact coil design, which subsequently means higher divergence of the B-field could be more beneficial.

Since the heater can be implemented in a different ways e.g. heater-less HC or RF hollow cathode,³⁰ therefore, it is not shown in the working principle schematics in Fig.18. Furthermore, a separation of ionization and acceleration process via ionization of anode gas with RF heating³¹ could be beneficial, but requires specific assessment with respect to a potential efficiency increase against invested RF power and increased complexity. Following list gives an overview of the advantages of introduced concept versus main EP technologies.

- Sustainable technology transfer from established EP systems (GIT, HET, HEMPT), specifically:
 - Power processing unit ($U_d \sim 300 - 1500$ V),
 - Hollow cathode emitter technology (e.g. LaB₆).
- Significant cathode lifetime increase (vs. WT20 HC of an AF-MPDT).
- Co-centric position of hollow cathode (vs. HEMPT, some HETs).
- No Hall channel required (vs. HET).
- Wide range of electric and magnetic field for manipulation of potential operation regimes (vs. HET).
- Good power scaling up to MW level, e.g. (vs. HEMPT, HET).
- Sustainable technology transfer of HTSC coils towards advanced EP systems (in the long term).³²

For the prove-of concept purpose a laboratory AF-MPD-EXHET thruster is currently in preparation for 2018 with a peak discharge power below 18 kW (< 450 V) and applied magnetic field of 400 mT (SX coil). Overall the concept behind AF-MPD-EXHET thruster seems to be very promising, regarding technology transfer, power scaling, lifetime, and application in power range beyond 100 kW (+ 500 kW and more).

V. Conclusion

The 100 kW class AF-MPD SX3 thruster has been successfully tested in steady state mode for more than 13 hours up to arc power levels of 115 kW. Experimental tests with variation of propellant distribution between electrodes have shown a good verification level with DFVLR results.^{11,12} Also, at constant arc power of 50 kW, the most efficient operations were achieved with anode mass flow ratio of 0.2 and relatively low total mass flow rate. Additional experiments have been performed with an arc power up to 115 kW, with a better performance of higher anode gas fraction at 100 kW of arc power. The most efficient operation of SX3 thruster has been achieved close to the onset regime at 65 kW, 400 mT, 428 A, and argon mass flow rate of 12+48 mg/s with the thrust of 2.16 N, specific impulse of 3700 s and thrust efficiency of 59 %. The influence of ambient pressure via re-entrainment effect is likely present and needs to be investigated at top conditions in near future. The thrust to arc power ratio of 32 mN/kW and power balance of heat losses imply that achieved performance is in realistic range, but is likely affected by the ambient gas via arc and thrust power balance. The single channel hollow cathode shows normal signs of erosion and proves the robustness for steady state operation at high magnetic fields. Additional variations of the hollow cathode are in consideration for future test campaigns. A conclusive summary of high applied magnetic field MPD devices is given, including DFVLR research and current IRS activities. A design of 5-10 kW pre-flight technology demonstrator model would be the most feasible way to validate performance of AF-MPD thrusters at lowest vacuum conditions and lowest ambient dependency ($\sim 1 \text{ kW/mgs}^{-1}$).

Furthermore, the concept AF-MPD-EXHET thruster is presented, which has a high potential of good performance range, scalability to high power levels and fast technology transfer leading to straight forward approach towards the pre-flight hardware, which would drastically impact space transportation sector. The results and conclusions presented in this paper show (under consideration of relatively low technical readiness level) a promising feasibility of an AF-MPD thruster as high power main propulsion system above 100 kW range.

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