The Investigation of Applied-Field MPD Thrusters on the International Space Station

Monika Auweter-Kurtz*, Gerd Krülle**, Helmut Kurtz *

*Universität Stuttgart, Institut für Raumfahrtsysteme
Pfaffenwaldring 31, D-70550 Stuttgart, Germany
Tel. +49 711 - 685 2375, Fax +49-711-6853596, e-mail : ep@irs.uni-stuttgart.de
**DLR Lampoldshausen, D-74239 Hardthausen, Germany,
Tel. +49-6298-28381, Fax: +49-6298-28458

Abstract

Electric propulsion for spacecrafts provides, because of the high specific impulse, an enormous gain in Δv and/or payload capacity, respectively.Of the different types of this propulsion the applied-field magnetoplasmadynamic thruster (AF-MPD) seems to be the best suited for the power range between 10 and 100 kW. Because of lack of missions and power available on S/C, the investigation of such thrusters was almost totally suspended for the last 20 years. It is a fact that these engines cannot be operated representatively in the laboratory because of the (high vacuum needed to exclude) unknown environmental interaction with the plume even at very low vacua. A space experiment is needed to provide proof of particularly I_{sp} and efficiency. With the ISS now a technical platform is available to resume this research. Therefore a technology experiment, MATEX, is suggested to investigate the technical limits of AF-MPD thrusters. A thruster is mounted on a half-autonomous platform, and the operation and eventually interaction with the S/C is monitored by an extensive diagnostic package.

Introduction

For missions needing high velocitiy increments, electric propulsion is the only way to achieve the goals in adequate time with an appropriate payload. For lower power levels (< 5 kW), today three kinds of continuous electric propulsion principles are under consideration or already deployed: ion propulsion and hall ion thrusters (SPT) for high I_{sp} duties, and thermal arcjet thrusters for the lower I_{sp} range.
With increasing power levels available in space, the (axisymmetric) plasma thruster with added electromagnetic acceleration (AF-MPD thruster) is for the first time considered for application owing to its considerably high thrust and remarkable specific impulse (as implied by thrust over propellant mass). While the self field MPD thruster, when continuously run, needs extraordinarily high currents (> 2000 A) to be effective and is limited on grounds of plasma instabilities to ca. 15 km/s, and, when operated in a pulsed mode, depends on complex (risky) electronics, the applied field MPD (AF-MPD) thruster efficiently operates in a power level of less than 10 to 100 kW which can be provided in large satellite or station missions today in discussion. Operable laboratory devices of such kind do exist and have been investigated for more than twenty years, particularly in U.S.A.[1-8], Germany [9-12], the former USSR[13,14], and Japan[15-184], where both theory, phenomenology, and technology have been intensively (but not conclusively) treated. The bulk of activity has taken place in the 60's/ beginning of 70's, and some effort is needed to resurrect these thrusters for a possible application. Despite the potential advantages of the AF-MPD, before a deployment on a S/C issues have to be solved like design and optimization problems, where solutions already exist but which still have to be verified in detail, and especially the important open question of an interaction of AF-MPD thrusters with the environment due to the fact that electromagnetic forces act outside of the hardware geometry sucking in ambient gas when available. This is the case in laboratory tanks which do not provide a sufficient environment to reach space representativity even with condensable propellants. As a consequence, in laboratory tests, there is anticipated a slight impact on thrust, and a considerable impact on I_{sp} defined as the ratio of thrust over fuel mass fed through the engine. Moreover, contamination problems (material and electro-magnetic) have to be seriously considered. An additional problem with the AF-MPD thrusters is that its dipole field is interacting with the earth's magnetic field, exerting a disturbing moment on the S/C.
Table 1 is summarizing the advantages and disadvantages of the different types of electric propulsion: For high power missions, needing high velocity increments, magneto-plasmadynamic thrusters with applied magnetic field are the best choice. They possess high thrust density, good scalability to high power levels and relatively simple design. The momentary disadvantage of a relatively low

development level is probably solved by the time high power installations on S/C are available.

In the following, after a short discussion of AF-MPD application potential, the operation principle, the nominal performance characteristics of AF-MPD's as well as their actual development status, critical areas, and open problems (as seen by the authors) are described, using the results of thruster hardware and experiments of the DFVLR (now DLR) in Stuttgart, Germany. A space experiment, capable of giving the required answers, is proposed.

Application Options of AF-MPD thrusters

Installations of medium power AF-MPD thrusters on spacecrafts depend on the availability of sufficient power, but new satellite generations like the Hughes 700 or the Aerospatiale AS 4000 series are planned with 10 kW plus, so that power for the propulsion system in periods when this power is not needed for the payload is available. This opens new fields of applications:

- Spiralling-up missions for GEO satellites. Spiralling-up of S/C to their destination orbit leads to large fuel savings compared to conventional positioning, which allow considerable expansions of the payload at a given overall S/C mass. These missions, however, were as yet excluded from consideration because of the long transfer times connected with electric propulsion. With higher power (which means thrust) levels, these transfer times will be reduced to become acceptable. New studies[19] show these advantages even with thrusters with relatively low I_{sp}.
- North-South-station- keeping. For big GEO-platforms the AF-MPD is advantageous for this task compared to other electric propulsion thrusters like ion engines or Hall-ion thrusters (SPT) due to the relatively simple construction and the high thrust densities or to arcjet thrusters due to the higher I_{sp}.
- Drag compensation. For large flying space structures with sufficient power installations like space stations, AF-MPD's are ideal for drag compensation, which would put aside or at least reduce the fuel (and hence weight) consuming need for reboost.
- Primary propulsion for deep space missions. Last but not least are forthcoming high power interplanetary missions, like a manned Mars mission, unconceivable without the assistance of high I_{sp}, high thrust propulsion. Also here again the AF-MPD is a most preferable candidate.

AF-MPD performance principle

Theoretical Basis of Operation

Thrust production. The design and acceleration principle of the AF-MPD thruster is demonstrated in Fig. 1. The thruster consists of a central cathode and a coaxial anode ring placed at end of a nozzle-like (isolated) hardware extension. The configuration is surrounded by a magnetic coil or permanent magnet in such a way that the produced ('applied') field forms another (magnetic) kind of nozzle opening downstream. The acceleration and energy production process is derived from generalized Ohm's law (for high degree of ionization) and the corresponding energy equation

$$\vec{j} = \sigma \vec{E}^* - \omega\tau(\vec{j} \times \vec{B}) / B$$

where

$$\vec{E}^* = \vec{E} + \vec{v} \times \vec{B} + (1/en)\nabla p_e$$

and

$$\vec{E} \cdot \vec{j} = j^2 / \sigma + (\vec{j} \times \vec{B}) \cdot \vec{v} - (1/en)(\nabla p_e) \cdot \vec{j}.$$

Consequently, the following mechanisms are active[4,7,9,11,17,20]:

- The Hall acceleration mechanism: as the discharge current crosses the applied magnetic field, azimuthal currents are induced which yield axial and radial Lorentz ($\vec{j} \times \vec{B}$) forces where the axial component directly accelerates the plasma while the radial component builds up a pressure hill. The magnitude of azimuthal currents (in relationship to the discharge current) depends on the so called Hall parameter $\omega\tau$, where ω is the cyclotron frequency of electrons being a linear function of the magnetic induction B, and τ is the collision time of electrons with heavy particles.
- Rotational kinetic energy is created in the plasma, resulting from the applied meridional current crossing the applied magnetic field.
- In addition, energy is added by Joule heating, which is converted into axial jet kinetic energy through the fringing magnetic field.
- The self field is normally negligible in the AF-MPD compared to the applied field.

All types of non-directed (rotational and thermal) energies can theoretically be converted into 'useful' axial velocities in the mechanical and the magnetic nozzle. The latter again operates through azimuthal currents that compensate, in the ideal case, centrifugal forces and overpressure.
The aerodynamic thrust due to the expansion of the plasma in a physical nozzle has also to be considered, its size depending on the geometry of the nozzle, the mass flow and energy input.

As a consequence, for AF-MPD acceleration to be effective, we need, before all, a strong magnetic field (B) of adequate shape, optimal degree of ionization (to have good coupling of mass to electromagnetic effects), and moderate particle density in the discharge region. Considering the acceleration mechanisms, a light weight propellant appears preferable for I_{sp} gain.

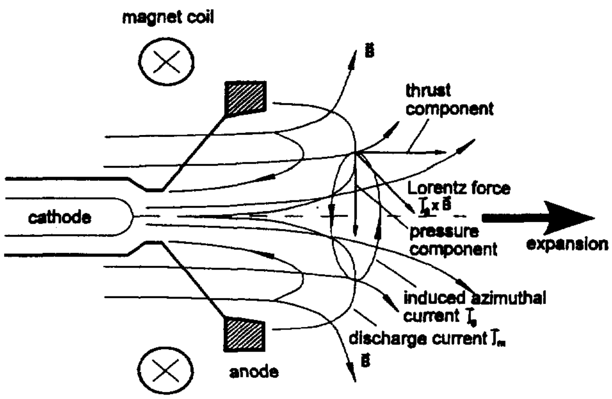

Fig. 1: Principle of an MPD thruster with applied magnetic field

Operational characteristics

As a general tendency, thrust and discharge voltage are rising with the strength of the magnetic field and the discharge current, see Fig. 2 for thrust and Fig. 3 for the discharge voltage.

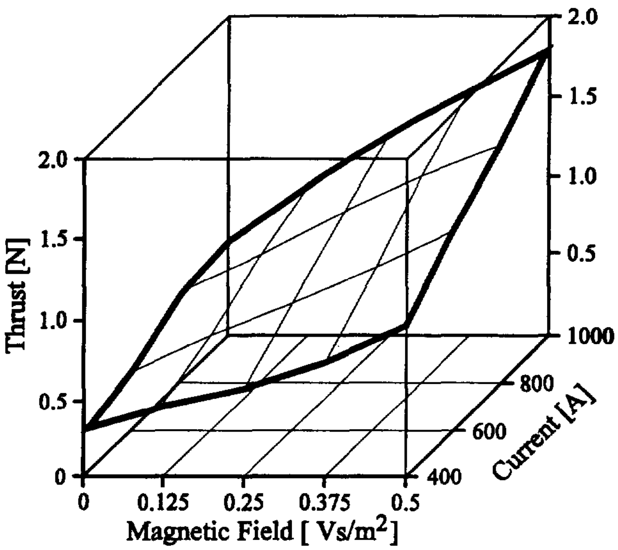

Fig. 2: Thrust as function of discharge current and magnetic field strength[10] (elevated power laboratory type X9, 100 mg/s argon, $p_a = 3.0$Pa)

Propellant mass flow has a more complex influence: while thrust is little affected (i. e. only the aerodynamic part), voltage tends to go down as mass is increased but depending on whether the mass is fed through the cathode or anode region ($\dot{m}_K$, $\dot{m}_A$,)[11,12]. Thrust seems more dependent on $\dot{m}_K$, while voltage is more influenced by $\dot{m}_A$ as shown in Fig. 3.

The role of $\dot{m}_A$ is not (or at least not primarily) to carry part of the current as an ion current as discussed above, but to guarantee a certain charge carrier density in the vicinity of the anode thus reducing anode losses and

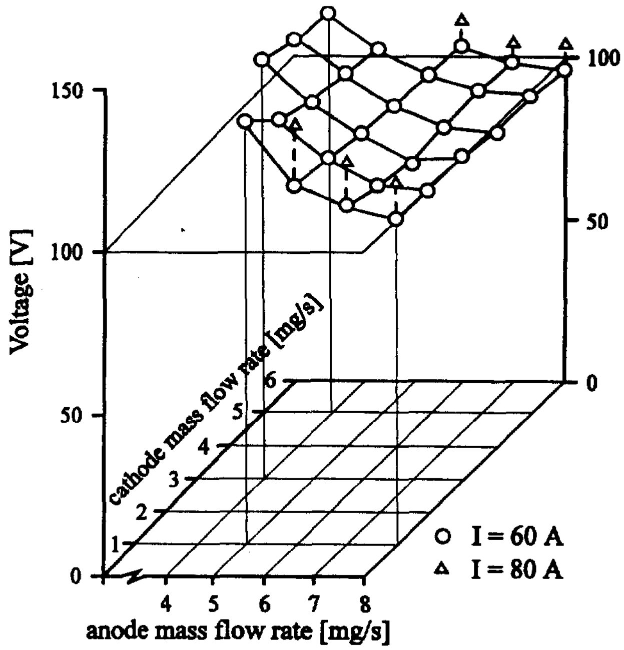

Fig. 3a: Voltage as function of anode and cathode mass fractions (preflight type X16, argon[12])

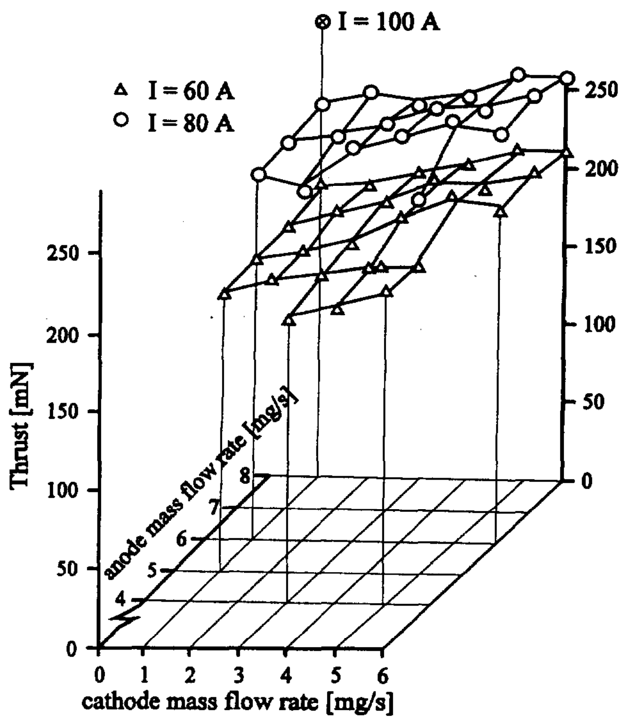

Fig. 3b: Thrust as a function of anode and cathode mass fractions (pre flight type X16[12]

eventual strong deviation from discharge axisymmetry[21]. Fig. 4 gives anode losses as a function of mass distribution [22]. (All the experimental evidence in this paragraph is taken from data from different laboratory thrusters of the DFVLR).

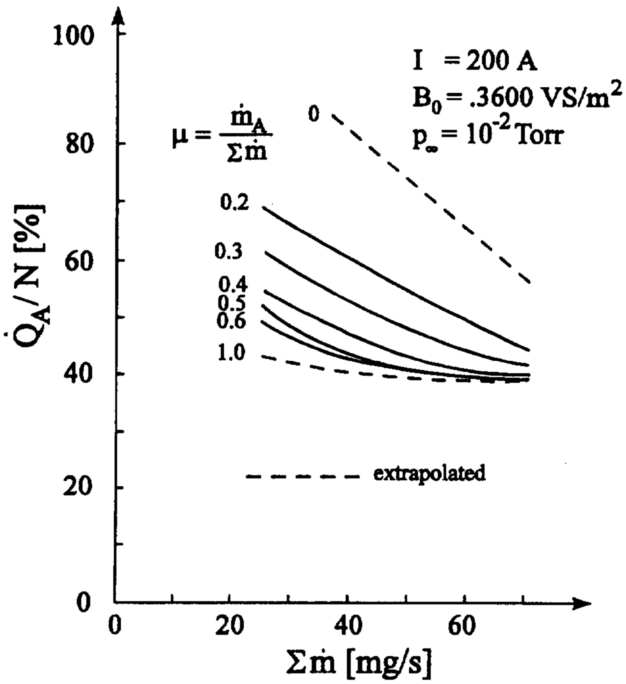

Fig. 4.: Relative anode loss as function of mass flow[22]

An important phenomenon which characterizes AF-MPD propulsion is the fact that a substantial part of the acceleration processes takes place outside of the hardware device. The discharge current whose distribution is a function of $\omega\tau$ (= $\sigma B/en$) bulges out far downstream as B/n increases. This fact has been experimentally[23,24] and computationally[11,15] verified. Fig. 5 shows measured current distributions at different magnetic field strengths. According to above dependency, the same applies at a decrease of density. That leads to the important influence of ambient pressure as demonstated in Fig. 6 where specific thrust (F/I) is shown to increase, in an extraordinary example, as the tank pressure (and therefore the gas density) is reduced (see also[6]). At still lower pressure, saturation may occur. The environmental influence on the overall process (participation of ambient gas in the acceleration process) is given, leading to an uncertainty of thrust and particularly I_{sp} determination. Even with condensable propellants, this effect is not reliably avoided due to the wide extension of the plume and the normally moderate dimensions of the vacuum facility.

The Hall acceleration mechanism requires an Hall parameter value much larger than unity in the anode jet to prevent the electrons from crossing the field lines from the cathode jet back to the anode. In contrast, measurements have shown[21,25] that azimuthal currents are not as high as expected from $\omega\tau$'s being in the order of 10 - 1000. The effective Hall parameter is, derived from

$$j_\theta / j_{m,\perp} \approx \omega\tau_{effective} \approx 3\ (-\ 8)$$

which is explained by anomalous diffusion of electrons across the magnetic field[3] and due to azimuthal non-uniformity of the discharge, so called "spokes", creating turbulence[21]. This effect must seriously be taken into account in an assessment of AF-MPD capabilities. As a consequence, e. g., the magnetic nozzle is not ideally effective, so that the plume mass is not fully contained within 'magnet walls', i. e. boundaries given by the 'anode magnet lines'.

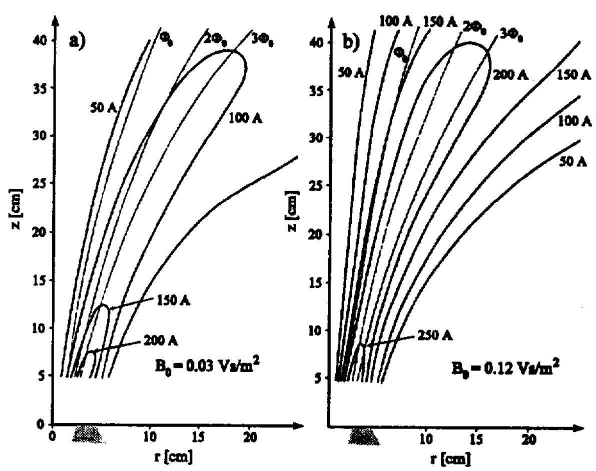

Fig. 5: Discharge current distribution at different magnetic field strength (X9, 100 mg/s Ar, p_∞ = 2 Pa)[24]

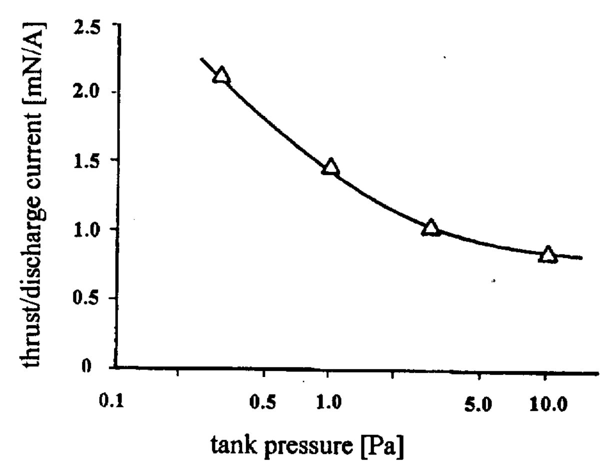

Fig. 6: Thrust per current as function of the tank pressure[12,22]

Hardware development status

The AF-MPD development to be resumed at the IRS will be based on one of the most advanced thruster types of the lower to medium power class (10 - 20 kW) built by the former DFVLR, which is shown as schematic in Fig. 7[12].

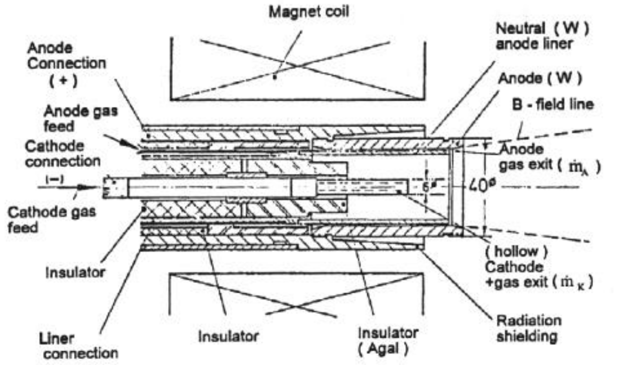

Fig.7: 12 kW radiat. cooled MPD thruster X16[12]

In this pre-flight type called 'X16', the propellant (noble gas) is fed through the hollow cathode ($\dot{m}_K$) and through a circular slit along the anode ($\dot{m}_A$) which in this case consists of a radiation cooled cylindrical tungsten body thermally isolated against the surrounding coil. The solenoid used in these experiments consisted of a non-flight type water- cooled copper tube winding operated at high currents; magnet power is not included in the data given below. The use of the secondary 'anode' gas was to prevent serious destabilization through anode starving i. e. lack of current conducting matter at the anode surface as a consequence of the radial pressure distribution. The device reached a thrust of 250 mN at a mass flow of 7 mg/s of argon which, neglecting the probable influence of environmental gas, yields an $F/\dot{m}$ of 36 km/s and an efficiency of nearly 40 % with ca. 12 kW electric power input. The other operation parameters at this point were: discharge current 80 A, voltage 145 V, max. magnetic induction 0.6 T, ambient pressure 0.05 Pa. Figs. 8 and 9 show the operable thruster model (solenoid omitted) and the thruster in action in the test chamber.

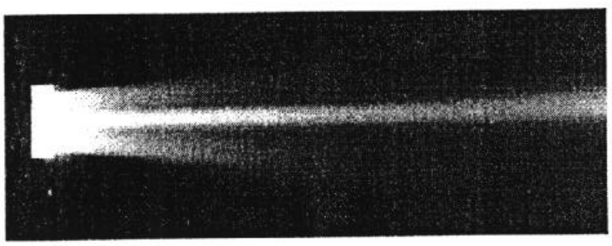

Fig. 8: Radiation cooled MPD thruster in operation[12]

Even if the functioning and optimization of AF-MPD is not completely solved, a considerable hardware status of preflight models is achieved.

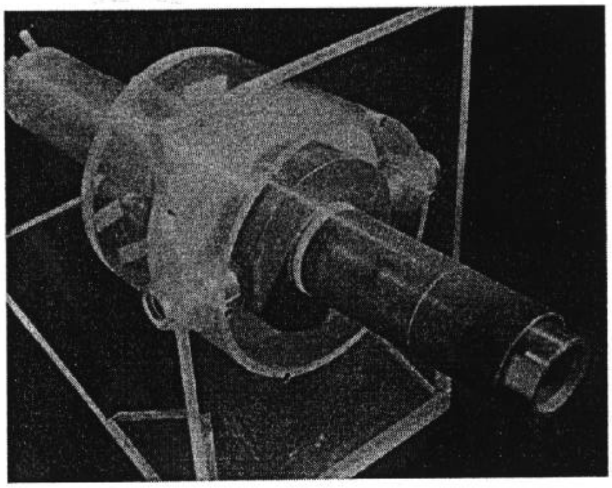

Fig. 9: Radiation cooled thruster X16 displayed in holder, magnet coil omitted

MATEX-Magnetoplasmadynamic Thruster Experiment on the ISS

As shown above, considerable interactions exist between the AF-MPD thruster and its respective environment:

- on one hand, the ambient pressure or gas density has a decisive impact on thruster performance;
- on the other hand, there is a danger of contamination of the AF-MPD environment - the carrying S/C - by thruster material (propellant or eroded material).

This rises following issues with regard to the real (space) performance:

How long will thrust increase with ambient evacuation? Will it reach a saturation level?

Will destabilization occur when the ambient pressure get lower and lower?

Eventually, what will the I_{sp} and efficiency in space come out to be?

At very low pressures, what will be the appearance of the thruster plume under the influence of the magnetic field?

How far will charged particles follow the field lines (a problem already tackled years ago by Harder[5])?

Will, in the extreme case, part of them turn back to the thruster and/or spacecraft thereby spoiling the thrust balance and hardware?

These questions have to be tried to be answered by advanced experiments as well as by theoretical treatment (CFD), which must include a comparatively large spatial area outside of the engine due to the far-reaching interaction of the aerodynamic field with electromagnetic effects that prevail and modify the aerodynamic character. Computer codes exist that can be adapted to this task, e.g. [26].

The final validation, however, must be provided by operation in space. This is why a space experiment is urgently needed. It is proposed here:

Experimental concept

A test of an applied field MPD thruster in space could prove the ultimate limits of the acceleration mechanism and would help to clear doubts about environmental effects of the thruster exhaust interacting with the magnetic field in far distance from the thruster.
To solve these questions, an experimental platform attached to ISS is suggested by Stuttgart University, the Magnetoplasmadynamic Thruster Experiment, MATEX. Since the power level of the experiment exceeds the possibilities of the experimental interfaces of the ISS, an dedicated battery package will provide the thruster power, the MATEX needing only the re-charging power and some additional power for the maintenance of the experiments like PCU, diagnostic package etc. Foreseen are cyclic operations of 15 min each, total number of 250, propellant argon, nominal mass flow 10 mg/s. The propellant will be carried in gas bottles as part of the experiment. Eventually, additional power will be requested for the magnet coil, if an electromagnet is used instead of a permanent magnet, which has to be defined after appropiate ground tests.
The following masses, size and volume are preliminary estimates according to previous space flights of other thruster experiments, the ion thruster experiment RITA on the EURECA and ESEX, a high power arcjet thruster experiment on a technology satellite of the USAF[27,28].

Preliminary mass breakdown in kg

Battery package	80
PCU	50
Propellant gas (Ar)	3
Pressure tank with propellant feed system	15
Thrust balance	20
Diagnostic package	25
Thruster including magnet	5
Experiment control unit	4.5
Total	202.5

Size (estimated):

MATEX will be mounted on a pallet as attached payload, the pallet size is estimated to 1x1.5 m with probe arms jutting out 1 to 2 m, the height of the packed platform 1x1.5 m (pallet size) x 1 m (depending on the thrust balance design and size, (diagnostic arms not unfolded).

Diagnostic package

The thruster experiment will be accompanied by a variety of diagnostics, in the moment the following ones are as yet considered:
- The thrust is measured by a thrust balance in form of a flexible platform, on which the thruster is mounted and the deflection of this balance is a measure of the thrust.
- The plasma plume of the discharge will be investigated for luminescence with a video camera, with electrostatic probes, mounted on probe arms, for electron temperatures and densities, and the total radiation of the plume with radiometer.
- The thermal mapping and control of the thruster itself will be performed by a CCD-camera and thermocouples.
- The electromagnetic noise of the thruster (EMI) is checked with EMI antennas.
- The magnetic field in the plume and the current distribution will be monitored by magnetic field probes mounted on probe arms.
- A possible solar cell contamination will be checked by TQCM probes at different positions and sample solar cells.

Interfaces with the ISS

Power: The thruster power is delivered by a battery package, for the re-chargings are no constraints in duration. The needed additio8nal power during experiment (for PCU, diagnostic package etc.) is estimated to ca. 100 W, the power requirement for the magnetic coil has to be defined.

Data: During the operation of MATEX the operational parameters plus diagnostic data are registered autonomously by the Thruster-Experiment-Control-Unit, which have to be transmitted to the ground station from time to time. During dormant time the status of batteries, propellant tank pressure, status of valves and control switches have to monitored. The experiment will be started from the ISS control center at times preferable to the ISS operation.

Assistance needed by the ISS crew: During the experiment no tools are required and the on orbit time is not restricted. The used gas is part of the experiment.
No crew assistance is required after start of the experiment but after the experiment a retrieval of the MATEX platform is desired for checking and refurbishment.

Conclusions

It has been tried to show that electromagnetic thrusters with applied field (AF-MPD thrusters) have a satisfactory pre-development status and can be considered for preparation of application. With regard to their operating parameters, they appear fully suitable for future auxiliary and primary missions of large spacecraft. Development for flight readiness and

prequalification can be achieved through advanced laboratory tests and computational verification anticipating some of the most relevant features of space performance; space qualification, however, can be attained only by a space experiment. Threfore the experiment MATEX is proposed on ISS.
The AF-MPD final development, due to the world wide experience in plasma techniques and technology, can be achieved in due time in a joint international effort of experts to bring this promising next generation concept to maturity. While starting this renewal of development for alternative space propulsion, and trusting that anticipated advantages are verified, it is hoped that future application will be adequately supported by both propulsion and spacecraft/station communities.

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