The "New Grid Systems for Ion Engines" Technology Project - Results and Conclusion

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Hans.J.Leiter* and Rainer Killinger
EADS Space Transportation GmbH, Möckmühl, D-74215,, Germany

Elisa Bonelli, Simone Scaranzin and Fabrizio Scortecci †
AEROSPAZIO S.r.l. Zona Industriale "SENTINO", 53040 Rapolano Terme, Siena, Italy

Marco Capacci and Maurizio Materassi‡
ALENIA LABEN Proel Via A. Einstein 35, 50013 Campi Bisenzio (Firenze), Italy,

Leonardo Biagioni§
ALTA Via A Gherardesca 5, Ospedaletto, Pisa, Italy

Niccola Kutufa**
AOES- BV Leiden and European Space Research and Technology Centre, ESTEC/ESA, P.O. 299, 2200 Noordwijk, The Netherlands

Horst Neumann and Michael Tartz††
IOM Leipzig, Permoserstraße 15, 04318 Leipzig, Germany

Davar Feili‡‡
University of Giessen, Heinrich Buff Ring 16, 35539 Giessen, Germany

Abstract: "New Grid Systems for Ion Engines" is a project in the frame of The European Space Agency ESA's Technology Research Program (TRP) aiming on a further improvement of grid systems for ion engines with respect to performance, lifetime and reliability. A consortium of European electric propulsion specialists works together on a project consisting of three phases. In the study phase improvement and validation of numerical tools for grid design was performed. In parallel, standard and advanced grid materials were investigated. From the most potential materials subscale grids were manufactured, tested and assessed. During the design phase a grid system for the BepiColombo mission and a subscale grid for future high specific impulse engines were designed and manufactured. Meanwhile the also the validation phase which contains the intensive endurance test of the grid systems is nearly completed. This paper summarizes the results of the three study phases and a first conclusion is drawn.

* EP Engineer, TP 42 hans.leiter@space.eads.net
† CEO Aerospazio s.r.l. , fscortecci@aerospazio.com
‡ , Capacci.m@laben.it
§ CEO ALTA, ,l.biagioni@altaspazio.it
** TEC-MPE, Niccola.Kutufa@esa.int
†† , michael.tartz@iom-leipzig.de
‡‡, 1st Institute of Physics Giessen davar.feili@physik.uni-giessen.de

I. Introduction

The grid system is one of the most important components of any ion thruster. Its design has significant impact on the thruster's key data as performance, lifetime and last but not least the engine's reliability. So it does not wonder, if the grid system is a permanent object of research and development activities, world wide.

In contrast to the simplicity of the basic function principle of a grid system the layout and design process is nevertheless challenging. For success the required know how covers the full bandwidth from "classic" space engineering technology up to the knowledge about specific aspects which are rather more from scientific nature.

Namely the understanding of the ion acceleration and the erosion processes over the lifetime demands for an understanding of electrodynamics, plasma physics and solid state science.

All these aspects are subject of The European Space Agency's initiative "New Grid Systems for Ion Engines". "New Grid systems for Ion Engines" (NGS) is a project in the frame of ESA's Technology Research Program (TRP). This comprehensive project aiming on significant higher grid performance which includes also lifetime and reliability is performed by a consortia of European space propulsion specialists under lead of EADS Space Transportation GmbH. AEROSPAZIO (I), ALTA (I), Laben (I), IOM Leipzig (G) and Giessen University (G) are the other team members. The approach of the project members is reflected in a project structure which consists of three phases:

- Phase I: Study Phase
- Phase II: Design Phase
- Phase III: Validation Phase

Phase I is dedicated to all the required numerical tools for grid design. In parallel, research in advanced grid materials is undertaken. This study phase is completed by a critical assessment of existing grid systems and an evaluation of in-flight experiences. Target of phase I is to establish "Grid technology readiness"

Phase II bases on the achieved "Grid technology readiness". The original goal was to design and manufacture two grids, one for ESA's BepiColombo Mission and a second one especially for the requirements of commercial geostationary satellites. Both grids were to be designed for typical European 22cm beam diameter ion engines. In parallel to the development of the two 22cm grid systems a third grid system on sub-scale level was to be developed for the demands of very high specific impulse. Presently, the overall power class of an European "High Specific Impulse Ion Engine" is not defined. Consequently design, manufacturing and test of a high specific impulse grid will be restricted on subscale level.

The *third study phase* is called "validation phase". Representative life tests over 1500h of operation with the 22cm grids have to demonstrate the achieved improvements in grid technology. One of the tests has to be extended for additional 1500h. The subscale high specific impulse grid will be validated in a 500h test. For all endurance tests the validation is not limited to behaviour and lifetime of the grids. These tests are also intended as a validation of the ion optics design and life prediction tools.

During the project execution it became evident, that the requirements for the BepiColombo mission and the requirements for geostationary satellites in terms of specific impulse and thrust require a nearly similar ion optics layout for both applications. Consequently, the study logic was redirected. It was decided to design and manufacture one grid system suitable for both missions. Instead of testing two different grids for 1.500h each, this one grid is to be tested for 3.000h. An additional test using an identical, but new grid system will be performed over 1.000h. In this test the evolution of the grid erosion will be studied in short time intervals instead of every 500h as performed in the 3.000h test.

Another redirection of the study logic concerns phase I (study phase). Some of the investigated materials were rated from great potentiality for the near and mid-term future. Although these materials were not applicable for design and manufacturing of a grid system within the time frame of this project, further investigations were undertaken. So the study phase was not closed and the work with the potential future materials was performed in parallel to the design and the validation phase.

The introduction closes with a description of the works-share between EADS and its partners. The listing demonstrates the comprehensiveness of the TRP project:

- Overall programmatic and scientific project management (EADS ST, D)
- Sputter experiments (IOM Leipzig, D)
- 100h Subscale tests of grids made from standard and advanced materials (IOM Leipzig)
- Development and manufacturing of boron coated molybdenum grids (ALTA; I)
- Optimization of ion optics of grid sets suitable for 175mN operation (IOM Leipzig and EADS ST)
- Optimization of High Specific Impulse Ion Optics (Alenia-Laben)
- Mechanical and Thermal layout of 175mN grid sets (EADS ST)
- Thruster integration and operation (EADS ST)
- 175mN Life test evaluation (EADS ST)
- Conduct 500h Subscale tests with High ISP Ion Optics (Alenia-Laben)
- Provide Test Services for 1500h life test (University of Giessen, D)
- Provide Test Services for 3000h life test (Aerospazio, I)

II. Results from the Study Phase

A. Materials for Ion Optics Systems

1. Scope

Up to know, two different material systems are *de-facto standard* for ion engines: Grid systems made *fully of molybdenum* and grid sets consisting of a *screen grid* made of *molybdenum* and an *accelerator* grid made of *graphite.* Moreover some groups try to establish carbon-carbon for use in ion engines. In addition, worldwide research is ongoing to improve the sputter properties of metallic materials.

In the frame of the "New Grid Systems for Ion Engines" project a two step approach is devoted to the research in grid materials.

At first, extended sputter experiments are performed. Although a lot of sputter experiments have been undertaken by various researchers there are still gaps in existing sputter data libraries. and there exist new advanced materials which are not yet investigated.

In a second step, 100h life tests on subscale level are performed for selected materials.

A challenging additional approach was undertaken to improve the sputter behaviour of molybdenum by a boron-carbon-coating. In addition to the sputter- and 100h life test an extensive research phase on the coating process is necessarily to be in introduced. More details are described in a separate section.

2. Most recent Data

The sputter yields of titanium, nitrided titanium and various kinds of graphitic materials like high-density graphite, pyrolytic graphite and Carbon-Carbon under xenon ion incidence have been investigated in dependence on ion incidence energy and angle. The set-up and measurement procedures are described in detail in [7].

The titanium sputter yield results are shown in figure 1. The sputter yields are found in good agreement with the semi-empirical approach of Bohdansky [2] and Yamamura [3] and the data of Rosenberg.

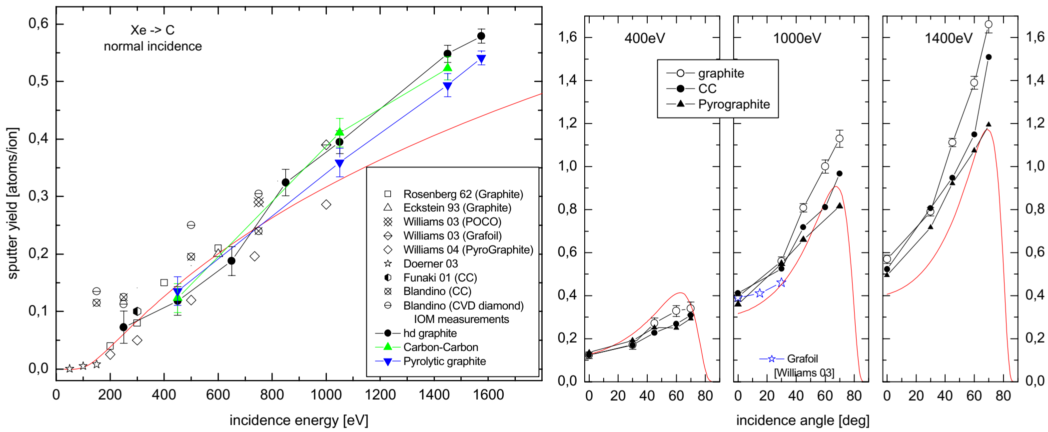


Figure 1 Sputter yields of graphite, Carbon-Carbon and pyrolytic graphite in dependence on xenon ion energy and angle. Solid lines are the semi-empirical sputter models of Bohdansky and Yamamura.

Nitriding of metals is suspected to reduce the sputter yield, a reduction up to 40% was recently reported [4]. In order to confirm these results and to check the applicability to enhance the grid lifetime, molybdenum and titanium samples were plasma and PIII treated for nitrogen implantation [5]. The sputter yield was determined in short measurement time steps in order to find out the effective implantation depth. A reduction of the sputter yield by 10% for nitrided molybdenum and 20% for nitrided titanium was found, however, the sputter-reduced layers were only a few micrometers thick, which was confirmed by measurements of the implantation depth by SIMS and ERDA. Consequently, this material modification seems not useful for increasing the lifetime of ion thrusters grids.

Graphite has one of the lowest sputter yields under xenon incidence, and therefore graphite is one favourite material for ion thrusters grids. However, the suboptimal mechanical properties of graphite encouraged to look for other types of graphitic materials with better properties thereby further benefiting from the low sputter yield. Carbon fiber-reinforced composites (CC) are manufactured by embedding carbon fibers into a carbon matrix and feature high-strength and high-stiffness. Pyrolytic graphite is manufactured by decomposition of a hydrocarbon gas at very high temperature in a vacuum. The sputter behaviour of these materials has been investigated.

Figure 2 shows the sputter yields of the various kinds of graphitic materials in dependence on ion energy and incidence angle. There is no significant difference observable between the various graphites. A strong advantage of CC and pyrolytic graphite over conventional graphite w.r.t. sputter yield, as it was stated earlier [6] could not be verified. Furthermore, no effect was seen of the initial surface topology of the samples which might be due to the rather long sputter times.

Summarising, CC seems to be the material of choice for the accelerator grid because of the low sputter yield and the extraordinary mechanical properties. More details on the sputter yield measurements and further data can be found in the separate paper [6].

3. *Subscale Tests*

Although the study of material data is a good base for selection of new materials, often disadvantages remain undiscovered as long as no grid sets have been built up with them. Problems which may effect the application of the particular material can occur during the manufacturing and assembling of the grids or during operation.

Therefore, thruster tests were performed in order to evaluate the thruster performance with various grid sets made from different materials and to identify potential problems mentioned above. A 100 h continuous operation under erosion-accelerated conditions allows for a characterisation of the erosion behaviour of the grid materials. The tests were performed on a sub-scale low-cost level within the small long-time test chamber at IOM employing a 4 cm thruster. 7 different materials have been investigated:

- Molybdenum
- Graphite
- Titanium
- Carbon-Carbon
- Nitrated Molybdenum
- Nitrated Titanium
- Boron coated molybdenum

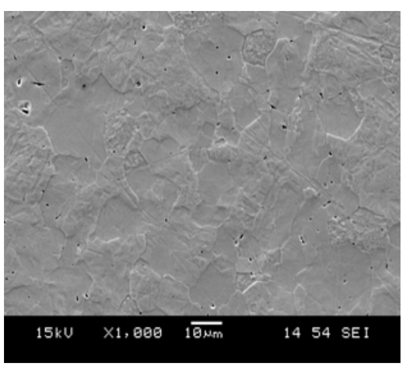
The tests are meanwhile completed. A detailed presentation of the results exceeds by far the scope of an overview article. Preparation of a publication describing the subscale tests in detail is progress. At this point it is stated that all 7 grid sets are fully operable. The Sputter data derived from the subscale tests confirms the expectations base on the sputter tests. Also it is worth to notice that the isolating coating on the boron-carbon grid does not cause problems during grid operation.

4. Boron-Carbon Coating for Ion Thruster Grid

A special activity on the development and testing of a low sputter-yield coating for ion thruster grids was pursued by Alta S.p.A. in collaboration with researchers from the University of California San Diego (UCSD). The goal of this activity was to demonstrate the feasibility of increasing the resistance of molybdenum to erosion by applying a thin coating of low-z material.

Various process parameters were explored during the project, in order to obtain a solid, continuous low-z layer, with good adherence properties also in the case of a high number of thermal cycles. Initial tests (run on small molybdenum samples) showed that good overall properties of a B-C layer could be achieved by using a suitable plasma enhanced chemical vapor deposition (PECVD) process, followed by heat treatment for generating a stable crystalline layer. Sub-micron thickness of the layer was achieved during the first series of tests.

The coated molybdenum generated in this way was exposed to a Xe plasma environment simulating what experienced in an ion thruster discharge chamber, and showed a significant reduction (by a factor of 10 or more) of the sputter yield when compared to equivalent uncoated samples.



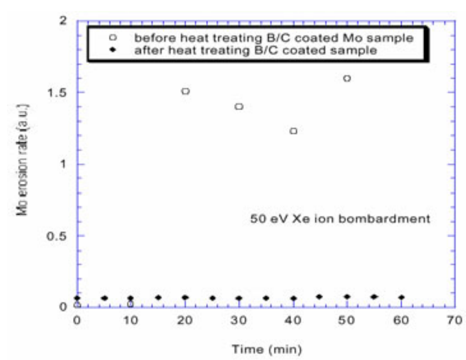


Figure 2a (left) SEM image of Moly sample coated with ~ 300 nm of B/C at high temperature (400° C) using carborane injection into Ar plasma.

Figure 2b (right) Comparison of erosion behavior of heat treated, and not heat treated, coatedMo samples. Before heat treating the amorphous films do not resist erosion for more than 10 minutes, whereas the crystalline films after heat treating resist erosion for more than one hour of accelerated erosion testing

The stability of the layer was positively checked against air exposure and against thermal cycling. The erosion measurements mainly confirmed the expected sputtering yield at low energies but unfortunately the first long duration results showed that even if the B-C sputtering yield is significantly lower than a pure graphite coating, the originally selected thickness was not enough the withstand long exposure to an energetic plasma.

An attempt was then pursued in order to increase the B-C layer thickness. The thickness was actually increased by a factor 5 but growth rate decreased with the thickness thus slowing down the coating process and limiting the thickness at about 1.5-2 µm. The layer's surface electrical resistivity appeared to grow esponentially with the layer's thickness thus creating an insulating barrier on the grid and could arise some concerns about the electric field distribution within the thruster. The tests carried out to improve the thickness by alternative processes showed a clear tendency to saturation even using an higher concentration of carborane. In this case problems with the stability of the layer were also encountered.

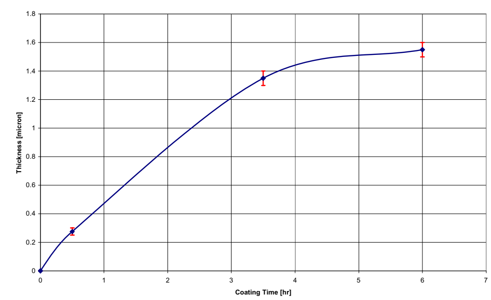


Figure 3 Deposited thickness for different process durations: a saturation phenomenon, probably due to the insulating behavior of the layer, is clearly present preventing the thickness from reaching higher values

Therefore the achievement of a thick layer does not seem a trivial task, requiring dedicated extensive experimental efforts to properly tune and optimize the process parameters (carborane density, plasma temperature, sample's biasing potential etc.) in order to obtain the desired characteristics of the layer.

B. Lifetime Simulation of the Ion Optics

5. General Approach

In the course of the NGS initiative the IOM grid lifetime simulation code has been reworked and extended to simulate the grid erosion evolution [8].

After one grid erosion simulation run is finished the erosion is simulated for a defined operation time step (typically 250 h), assuming constant beamlet and erosion parameters during that period. The grid surfaces are modelled as point chains. Each surface point is moved according to the local erosion rate. Then the simulation is started with the new grid shape, repeating these iterations until either the defined operation time is reached or the grid is substantially destroyed. During these iterations the *validity of the EBS limit is checked*. Variations of the operation parameters can be applied according to the particular mission profile. The time step should be adapted to the specific problem and chosen not too large so that the change in the grid geometry and their effect on the beamlet remains small.

6. A Systematic Subscale Life Test

In order to validate the lifetime modelling the erosion data of the subscale lifetime test performed at IOM using a 3 cm ion source was evaluated. The ion source operated with a self-aligning three-grid system for 2.800 h with frequent grid inspections where the hole diameters of all grids were determined .

Figure 3 shows the good agreement between measured and simulated accelerator grid hole diameters. The focus of the accelerator grid erosion shifts with operation time towards the downstream part of the grid hole, furthermore,

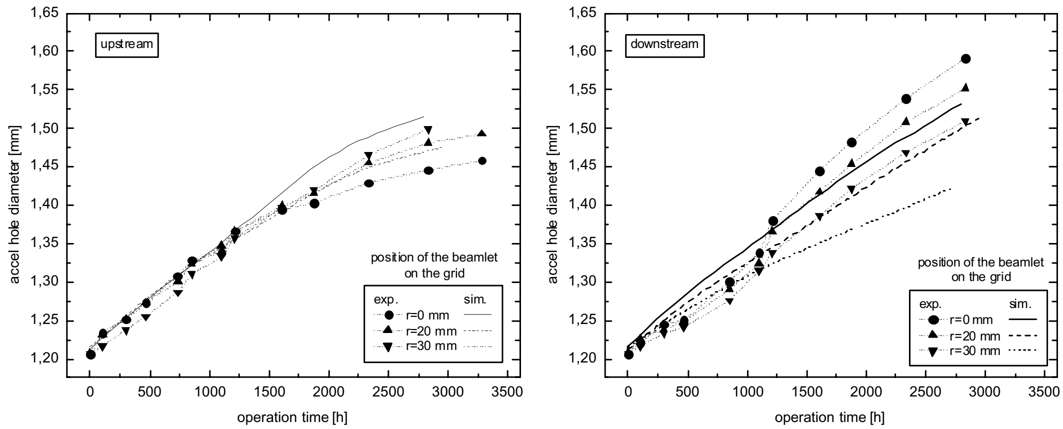


Figure 4 Evolution of the accelerator grid hole diameters upstream (left) and downstream (right), comparison of measured and simulated data.

the erosion rate reduces with time. The decelerator grid erosion was found to be very low as observed in the experiment. Extending the erosion to the end-of-life (assumed when the hole diameter of the accelerator grid hole reaches that of the screen grid hole), a lifetime under these test conditions of 8.000 h is determined which is mainly due to the very low mass utilisation efficieny of 47% which was intentionally chosen for this accelerated erosion lifetest.

An interesting detail was reproduced by the erosion. In the grid inspections counterbores were found surrounding the accelerator grid holes in the beam centre. A significant amount of erosion is found in the simulation at the plasma face of the accelerator grid which leads to a formation of such counterbores (cf. figure 6). At lower plasma densities where the beamlet becomes smaller, no charge-exchange ions are found at the upstream face of the grid.

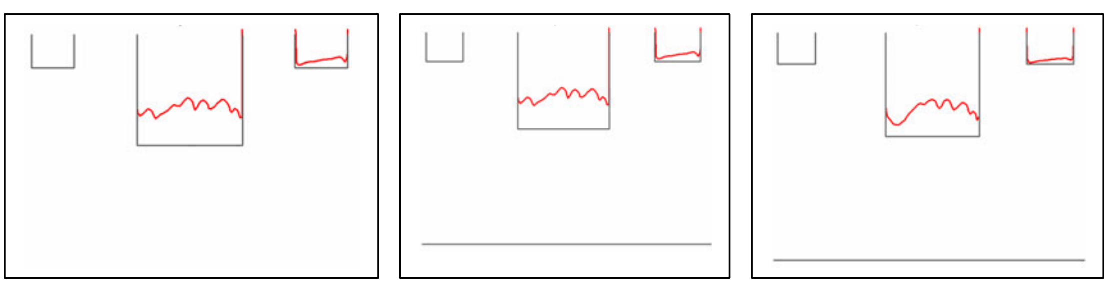
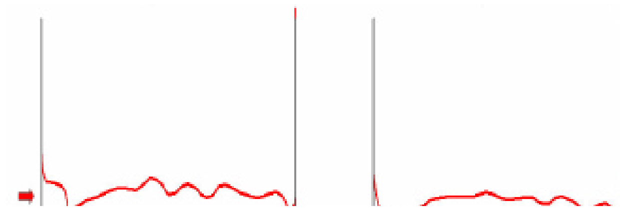


Figure 5: Simulated shape of the grid holes

Figure 6 Simulated shape of the accelerator grid holes after 1.300 h showing the counter bore in beam center (left) and no such structure at beam edge (right).



7. A real Ion Thruster and the IOM life prediction code - RIT 10 ARTEMIS

The dynamic simulation was also applied to evaluate the erosion data from the RIT-10 lifetest for ARTEMIS which was performed between 1998 and 2002. The ion thruster accumulated 20.000 hours of operation. During 6 maintenance phases the hole diameters of the accelerator grid were determined by mechanical hole measurement devices. For that the grid system was not dismantled. With the RIT-10 plasma profile obtained from earlier measurements the hole evolution was simulated at 4 radial positions on the grid (beam center, 1/3, 2/3 radius and beam edge). However, it was found that the first 2 beamlets do not differ significantly.

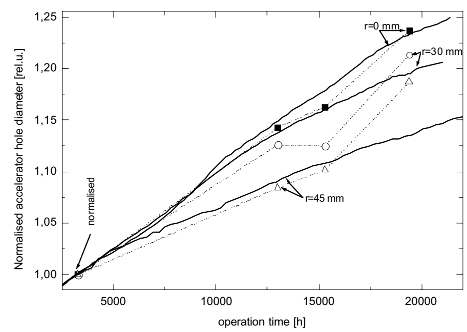


Figure 7: Evolution of the accelerator grid hole diameters (normalised to 1.0 at 3.000 h) with time in comparison with lifetest results.

Figure 7 shows the simulated accelerator grid hole diameters which coincides with the experimental data. The model yields a decrease of the accelerator grid current by 15% over the 20.000 h operation in good agreement with the lifetest data. Because of the rather high accelerator voltage EBS does not occur during the test.

After 20.000 h lifetest the grid system was already in good health far away from end-of-life. The simulation was proceeded to estimate the lifetime of the RIT-10 ARTEMIS grid configuration. Assuming as EOL criterion the equal hole diameters of the screen and accelerator grid which is quite conservative, the lifetime is 35.000 h.

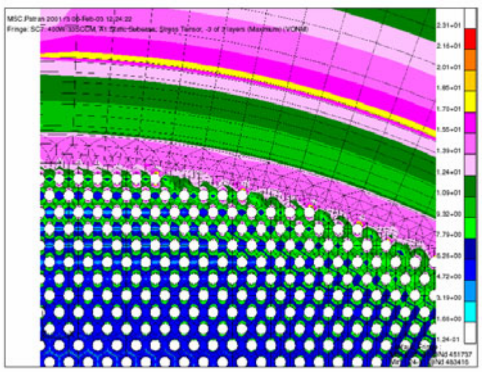
III. Results from the Design and Manufacturing Phase

A. Design and Manufacturing of a Grid for BepiColombo and Geostationary Satellites

Regarding the requirements for ion engines operated onboard geostationary satellites and the requirements for the BepiColombo-Mission identifies the requirements for the geostationary satellite application as a sub-set of the ones for BepiColombo. The typical thrust for geo's of ~150mN is contained in the thrust range for BepiColombo (70-150mN). The demand for the specific impulse is nearly similar from the point of ion optics design (4.000s vs. 4800s). On the other hand the total impulse of 1.4 x 10^7 Ns for BepiColombo exceeds the requirements for the geostationary satellites significantly. Moreover the thermal constrains for a thruster operated onboard the BepiColombo spacecraft are considered as the most challenging ever applied to an ion engine.

In consequence a design approach was chosen which bases on the BepiColombo requirements. For selection of the ionization principle of the thruster superiority of the radio-frequency ionization, originally invented by H.W.Löb at Giessen University (D) and commercialized by EADS ST over bombardment type engines is evident. As rf-thrusters require no life limiting cathode system in the main discharge and no sputtering of discharge surrounding thruster parts occurs, the life limit of an rf-engine reduces to the acceleration grid erosion by charge exchange ions. So the further development was focused on a grid system for the EADS ion engine RIT-22.

The design process of a grid system for RIT-22 was completed in January 2004. In summer 2004 the grid system was manufactured and all environmental tests including the vibration testing have been successfully completed (Fig)



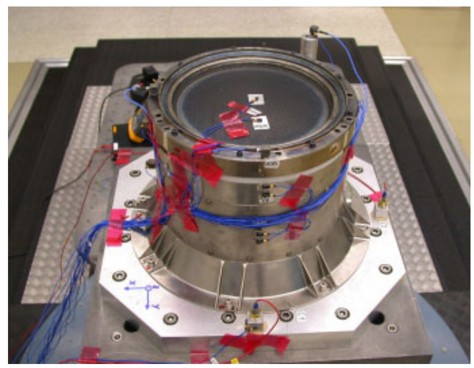


Figure 7 FEM Analysis of the grid system (accelerator) and grid system mounted on RIT-22 ion engine after vibration test

B. High Specific Impulse Ion Optics

The ion optics design for a high specific impulse ion engine as developed by Alenia-Laben was previously described in [ref]. During the design process 4 different layouts were investigated and assessed. Also a trade of between a two grid and a three grid system was performed. Although a three grid approach offers small advantages in respect to the beam divergence and grid erosion a two grid system was finally selected due to the simplicity and robustness. The ion optics layout is capable to deliver a specific impulse of 7.500s operated with an RMT ion thruster from Alenia-Laben. Operated with a RIT-22 ion engine of EADS even higher specific impulse is feasible. The identified geometry is summarized in the table 1.

IV. SCREEN GRID			ACCELERATOR GRID		
Material		Mo	Material		Graphite
potential [V]	Vs	5500	potential [V]	Va	-660
thickness [mm]	Ts	1,2	thickness [mm]	Ta	2,7
hole diameter [mm]	Ds	6	hole diameter [mm]	Da	4,2

Table 1 Dimensions of Grid System for High Specific Impulse

The single grids are mounted to a "Grid Sub-Assembly" (GSA). Finally the GSA is mounted on the RMT thruster. Holes on the Molybdenum (Screen grid) and Graphite disk (Accelerator Grid) have been realized through laser drilling techniques using a Nd-Yag laser. The Screen grid has been then brazed to the grid holder whereas the Accelerator grid has been aligned and fixed to the GSA through proper designed HV holders.

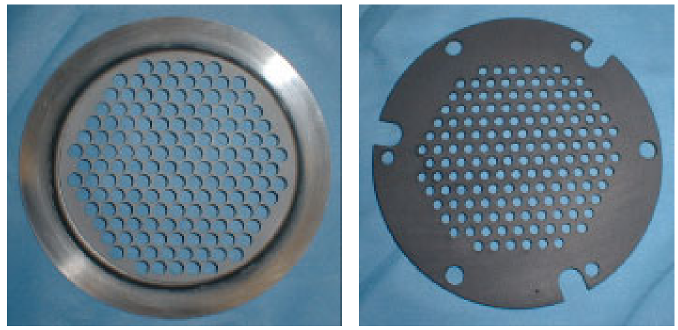


Figure 8

Screen and Accelerator Grid for High Specific Impulse on Sub-Scale Size

V. Results from the Validation Phase

End of December 2005 the endurance test of the grid system for BepiColombo and geostationary satellites was started in the new AEROSPAZIO s.r.l. test centre located in Rapolano Terme (I). Since that, the ion engine has accumulated more than 2.500h of operation within less than 5 months. In May 2005, the test was interrupted for the integration of a new designed beam target. A new block of 500h testing was started in the in the second week of July. Less than 4 weeks later this test block was also successfully completed.

A. Test Facility and Test Setup for Endurance Testing I

The facility consists of a horizontal stainless steel cylinder 11.5 m long, diameter of 3.8 m, for a total volume of 120 m^3[8]. The pumping system is made of:

a 1^{st} stage consisting of a roots blower backed by a rotary pump;
a 2^{nd} stage consisting of a turbomolecular pump backed by a dry rotary pump;
a 3^{rd} stage consisting of two cryopumps (20.000 l/s nominal pumping speed);
a 4^{th} stage consisting of a special system of panels cryocooled by six Cold Heads and Liquid Nitrogen baffles, specifically designed to pump Xenon.

A water cooled beam target is mounted at the chamber end. The target is covered with pure graphite plates to minimise sputtering toward the thruster. The interior of test facility is also fully lined with pure graphite panels.The thruster is placed close the Xe-cryosystem so as to fire along the chamber axis having a free firing length of 7.5 m and a free volume of 80 m^3. A rotating semicircular boom is installed inside the chamber so as to describe a hemisphere with a radius of 1 m, in front of the thruster. The beam diagnostics include Faraday Probes and Retarding Potential Analysers. The angular position accuracy of the probes is better than 0.5 deg, the radial distance accuracy less than 0.1%.

The RIT-22 Ion engine is operated with a Test Power Supply (TPS) developed by EADS ST. The TPS provides al required voltages for the thruster rf-discharge and the neutralizer. It controls a set of commercially available flow controllers and a flowmeter. A computer controls all TPS devices and is capable of an autonomous operation of the thruster including event handling for unexpected exceptions ("beam out", …). Moreover the TPS provides an ISDN interface for remote control from all over the world.

B. Test Results from Endurance Testing I

The endurance test was performed on the 175mN thrust level which is higher than the typical thrust (75-150mN) during the BepiColombo mission and the standard 150mN thrust level proposed for north south station keeping of geostationary satellites (at the later the available electric power onboard the satellites determines the highest thrust level). Although the 175mN operation is more stressing for the engine than operation with the typical requirements of mission the engine showed an exceptional stability w.r.t thrust and beam out rate. The beam out rate is extremely low, phases of more than 6 days without any beam out were observed. The thermal design of the engine together with the radio-frequency principle for ionization offers the option of "open-loop" engine operation. Simply setting the rf-power to a fixed value leads to a thrust stability with a deviation lower than 0.3% from the initial thrust level.

The operation on constant thrust level was interrupted for characterization tests including performance-, electron-back-streaming-, and perveance tests. All tests confirmed that the thruster design is in accordance with the BepiColombo mission requirements. All characterization tests were performed by EADS personnel operating the engine from Lampoldshausen (D) using the ISDN remote option of the test power supply.

In total 5 optical inspections of the grid erosion were performed. For that, the test is interrupted and the RIT-22 thruster is dismounted from the test facility. Than, the grid system as one component is removed from the thruster. Using a high resolution CCD camera, hole diameters on 61 different positions were measures from each side of the grid system. As the grid system remains one component during the inspection, the alignment of the grids is guaranteed. The agreement between the measured erosion and the calculated erosion performed by IOM Leipzig is excellent. The life prediction after 3.000h of operation indicates compliance between the measured erosion and the BepiColombo total impulse requirement of 1.4 x 10^7 Ns.

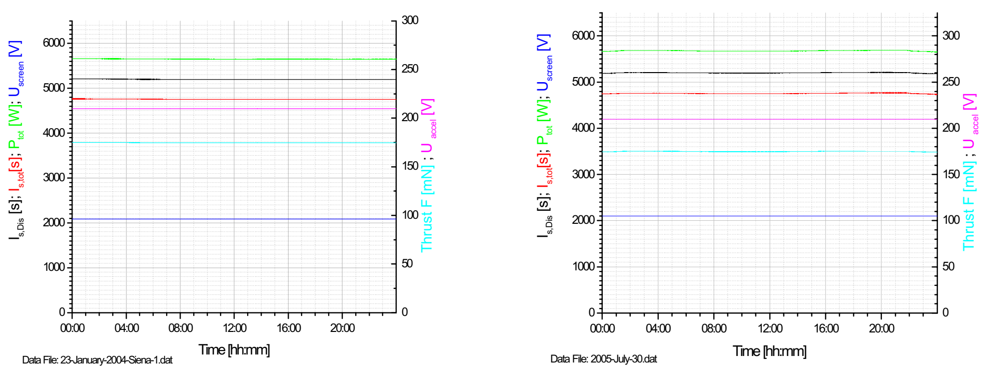


Figure 9 Typical daily data sheets from the 3..000h endurance test with the RIT-22 Ion Engine: Left January 2005, right: July 2005, last day before switching-off the engine for 3.000h grid inspection

C. Endurance Testing II - A Short Interval Grid Life Test

The 3.000h endurance is rated as a full success by the study partners. Proper operation of the grid system, the thruster, the power supply electronics and the test facility were demonstrated. Moreover erosion prediction and measurements are compliant.

Conducting an endurance test is always a compromise between risk mitigation (and also costs) on the one side and obtaining sufficient data on the other side. One has to be always aware of the potential risk of a damage of the ion engine or grid system during each grid inspection. Also the grid inspections are time consumptive. Thus EADS ST performed the first 1.500h as one block to ensure a valid life demonstration. The next inspections were conducted in intervals of 500h. Erosion measurements and predictions are compliant with the predictions for each grid inspection. Nevertheless EADS ST together with the IOM Leipzig aims on a further validation of the ion optics tools for design and life prediction. Now the first 500h of operation are subject of validation. The test plan is shown in Table 2. Compared with typical endurance tests the inspection intervals are short.

Interval No	Time	Accum. Time	Status
1	40h		completed
2	80h	120h	completed
3	120h	240h	in progress
4	160h	400h	
5	200h	600h	

Table 2 Test plan for Short Term Interval Test

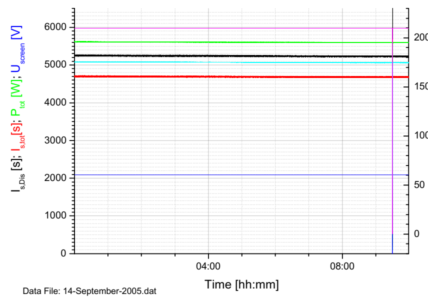


Figure 10 Data Sheet from Short Term Interval Test

The test is performed in the Giessen University Jumbo Test Facility (for details see ref [16]. In the meantime the first two segments were completed and the third segment is ongoing. Although the two test facilities, Giessen University and Aerospazio Technologies are different w.r.t. size, equipment and pumping concept, the engine shows up to now the same stability an performance in the much smaller Giessen test chamber.

D. High Specific Impulse Ion Optics

Study partner Alenia-Laben performs the 500h life test with the high specific impulse ion optics system on sub-scale level. This test contains also a complete characterization of the grid system. The first tests indicate that the new ion optics meets the expectations. The test is in an early stage, so no final assessment is possible.

When dealing with highest voltages on the grid system the electron back streaming limit. (EBS) is besides over-crossing the most critical parameter. The result of the first measurements is presented in Figure 11. Operating with a beam voltage of 3.5kV a accelerator grid voltage of ~ -300V is sufficient to suppress EBS efficiently.

Figure 12 Alenia-Laben vacuum test facility for ion thruster endurance test

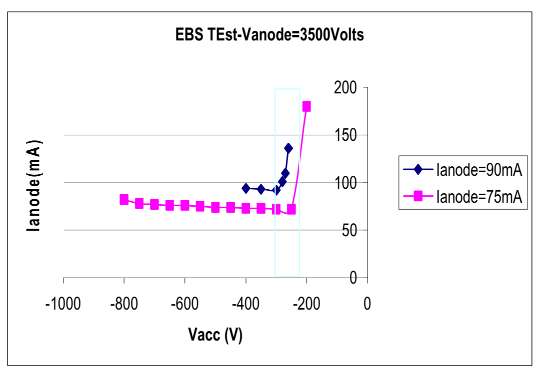


Figure 13. EBS Test with High Specific Impulse Ion Optics

VI. Conclusion

The "New Grid Systems for Ion Engines" is one of the most comprehensive approaches to improve grid technology known to the authors. In contrast to other projects and research work that is typically limited to particular aspects of grid technology the NGS project covers the full bandwidth from fundamental research to engineering and application. On the one side it contributes a lot of new and missing data to the electric propulsion community, on the other side a complete grid system for a real application is presented. This grid design exceeds by far the study level. Environmental tests, including vibration test, high radiation exposure and a 3.000h endurance test underline the level of development.

Assessing the result of the 3.000h test, which demonstrates compliance with the challenging BepiColombo requirements, confirm the chosen approach. Bringing together the most experienced specialist it the specific fields of electric propulsion was the key to success.

This publication is intended only as an overview, pointing out some of the interesting aspects. For detailed information several publications are available and others will follow soon.

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