µFCU - A Miniaturized Flow Control Unit for Xenon

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Abstract: The AST Advanced Space Technologies GmbH has developed a new type of miniaturized flow control unit for electric propulsion systems. The new design uses solenoid valves in pulse width modulation to control the gas flow. The fluidic interconnection between components is realized by a flow path board with integrated microchannels. The flow control range of the µFCU can be designed for flows from 0.01 sccm to 100 sccm. A standard µFCU configuration for common electric propulsion systems (GIT, HET, HEMPT) comes with two independently controlled outlet flow lines with different flow ranges for thruster and neutralizer. The µFCU includes 5µm inlet and outlet filters to protect the FCU. The all-welded device has a total weight of 62 g and fits into a 54 x 46 x 25 mm geometric envelope. During a development and test program the performance and lifetime capabilities have been demonstrated.

I. Introduction

A consortium of five European partners led by AST Advanced Space Technologies GmbH (AST) developed a new miniaturized flow control unit µFCU. The development project has been funded by the European Commission in the 7th Framework Program.

The project started in December 2012 and ended in September 2013. During this 22 month project the development was strictly objective driven. Six major objectives had been defined at the beginning of the work and refined during the project.

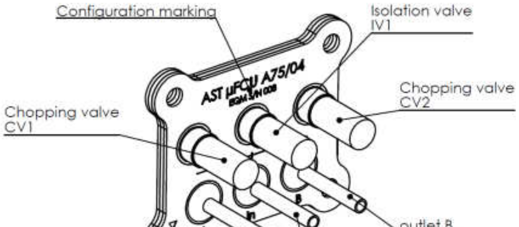

Figure 1. Miniaturized Xenon flow control unit "µFCU"

II. Objectives

Electric propulsion (EP) is a key technology for future space missions and satellites. Most of the used or planned EP systems need controlled and steady flows of Xenon gas to supply the thrusters and neutralizers. Today, flow control units (FCUs) have a typical mass of about 400 grams to one kilogram to supply one thruster. Assuming spacecrafts (S/C) with up to 24 thrusters for fine pointing capabilities like LISA, the FCUs are significantly contributing to the mass and power budget. Such future missions have low S/C masses. Consuming such a large portion of the total system mass, the use of a EP systems with actual FCUs is impractical.

Objective 1: FCU system mass less than 100g per thruster (thruster + neutralizer flow line).

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Today, Europe has no own high TRL technology for miniaturized flow control units covering a broad flow range. Even for normal sized FCUs the design of most suppliers rely on valves with US origin due to the lower leakage rates compared to European solutions. This brings Europe into dependency from external countries. Therefore a flow control unit for EP systems has been rated as critical space technology. The proposed new µFCU concept bases on European sourced components only. These components yield at least the same performance as such from US competitors or even outperform them.

Objective 2: Only components of European origin.

For missions like telecom satellites the system operational time may exceed 15 years. As result, the propellant loss due to leakage must be limited to a minimum. At the same time it is an advantage for system integration, if the operational temperature range can be increased above +90°C.

Objective 3: Achieve internal leakage rates below 10^{-6} *scc/s GHe over lifetime and extend temperature range beyond +90°C.*

The cost effective development and production of a flow control unit is only possible, if the full market potential is addressed. Therefore the basic design of the FCU shall be able to supply micropropulsion systems (<1mN thrust) as well as thrusters and neutralizers for satellite station keeping (typ. 50-100 mN thrust). If it is not possible to develop one FCU covering the full range, a scaling method shall be engineered to adjust the flow rate by design. For the development at least 10 sccm Xe shall be demonstrated with design margins reserved for at least 50 sccm.

Objective 4: Demonstrate the operation with at least two flow ranges a) 1.5 sccm F.S. Xe, b) 10 (50) sccm F.S. Xe

The emerging missions with low thrust and fine control requirements like LISA need a capable micropropulsion system. To have a chance in the selection process as a candidate technology at least TRL 5 is required. This would include a prequalification activity to verify that the FCU fulfills its requirements against a generic specification.

Objective 5: Reach TRL 5

The performance of an unit has to be rated in the context of the embedding system. Development and system cost grow with system complexity and the number of interface requirements. Even if hard to measure, the simplicity of a design is one of the keys to acceptance in space business. For a device like a flow control unit simplicity means, it shall be modular and shall have a minimum of well defined interfaces that can be satisfied by state-of-the-art equipment.

Objective 6: Use a modular concept and keep the design simple.

III. Design Description

The µFCU project bases on a "spin in" development approach of ITAR-free European components. The partners provide technologies and components that have been developed for high performance and high reliability ground applications. An advantage of the use of existing technology is a cost and time reduction for the development. A second advantage is the experience from development, production and application gained by the manufacturer during decades. Furthermore a good data base from terrestrial applications is useful to estimate component reliability and production yield. Nevertheless some new aspects that should not be underestimated are added to a design if components are integrated into a system and if they are prepared for a space application. Within the scope of the µFCU project these technologies have been converted to space application. This conversion covers the exchange of materials to equivalent space proven types, the application of processes like cleaning and cleanliness control and an intensive test and verification campaign. This campaign was carried out on component and unit level.

Figure 2. µFCU EQM 02 in comparison to the size of an USB stick

During the development phase the production and assembly processes have been mastered and transferred to the unit level. After the development phase, two EQMs have been manufactured in mid of 2013. EQM 01 executed performance tests and thermal vacuum tests. EQM 02 was subject to performance tests and vibration tests and is currently in a proof pressure test followed by a thermal vacuum test. With the end of the thermal vacuum tests EQM 02 has performed all qualification relevant tests to qualification levels except lifetime test.

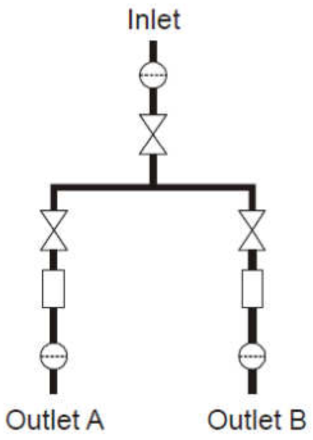

Figure 3. Baseline µFCU schematic

A. The Baseline Design

The term "µFCU" covers on the one hand AST's technology to design and manufacture a miniaturized flow control unit based on conventional component technologies like solenoid valves. With this technology different types of flow control and management systems can be set-up. On the other hand, it stands for the baseline design of a Xenon flow control unit with one inlet flow line and two outlet flow lines in the context of this publication.

The µFCU has two independently controlled flow lines with commandable flow rates. The number of lines is sufficient to supply either two independent thrusters or one thruster/ neutralizer pair (SPT, HEMPT, RIT). For configuration examples please refer to Figure 7. The µFCU has no sensor element to keep the system complexity low (objective 6) . The control loop can be closed using a signal from the thruster like the anode current (SPT, HEMPT) or the deviation from a optimal operation point (RIT). Such a control is commonly used in state-of-the-art electric propulsion systems.

The FCU is supplied with xenon gas (or other noble gases) through a inlet port. The inlet is protected by a 5µm stainless steel mesh filter. The flow into the µFCU is established or stopped by the inlet isolation valve (IV). Behind the isolation valve the flow splits into two branches. In each branch a chopping valve (CV) is operated in a pulse width modulation (PWM) or frequency modulation (FM) to control the average flow. Each valve can be controlled individually so that compared to some other designs the flow ratio between both outlet lines can be varied. The pulse flow from the valve enters a microchannel structure. The channels, acting as flow restrictor, form together with cavities a fluidic low pass filter to eliminate the flow ripple at the outlet. The flow channels and the cavities are embedded in a planar structure called "flow path board (FPB)". This FPB can be compared to a PCB in electronics. It interconnects the (surface mounted) components like filters and valves and provides the resistive and capacitive elements.

Both output paths are filtered by 5µm particle filters. The particle filters in inlet and outlet lines isolate the interior of the µFCU from contaminations during integration handling e.g. line welding. Particles trapped from outside on the filter mesh can be flushed with isopropyl alcohol.

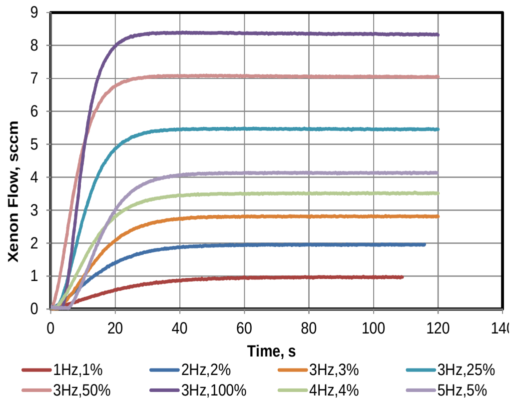

Figure 4. Settling of the Xenon flow after a step command. No flow ripple detectable.

The valve manufacturer's heritage in building valves for leakage testers contributes to ultra low internal leakage. Therefore all valves can act as isolation valves. Actually the same valve type is used but with different lifetime switching requirements. By this, the concept shows a double serial redundancy against propellant loss. The internal leakage of the µFCU is specified to be better than 10^{-6} sccs GHe. Typically values achieved during test campaigns are even one order of magnitude lower over full life.

The PWM/FM operation shows a number of system advantages compared to proportional valves[2,3]. The PWM/FM valves are completely switched open or closed during one cycle. The switching is robust and has no drifting working point compared to the proportional valve. The drift of the working point is critical for the control of small flows in environments with large temperature changes.

Also the driving electronics benefits of the reduced requirements if a simplex switched voltage (20V...24V) is required compared to a precisely controlled analog current. Such precise control yield challenges if drifts and aging shall be compensated for a lifetime of 15 years on a telecom satellite.

The major drawback of state-of-the-art PWM/FM controls is the large flow ripple introduced by the low frequency on/off cycles[4]. The typical sound of the operation also triggered the nickname "bang/bang". The µFCU development was able to overcome this drawback by introducing a higher chopping frequency typically in the range between 1 Hz and 5 Hz. Combined with a fluidic low pass filter element embedded into the flow path board, the flow ripple at the outlet vanishes (Figure 4 and Figure 9).

B. Component Development

1. *Valves*

A higher chopping frequency drives the number of lifetime switching cycles. As example, a µFCU running with 3 Hz average frequency for 20 000 hours activates the chopping valves for 216 million cycles. The valves used for µFCU utlilize a very advanced plate anchor technology without bearing friction compared to a standard plunger. Only the small bending of a precision spring, the magnetic forces in the coil assembly and the hit of the armature onto its rest introduce a mechanical stress.

The major wear mechanism is linked to the abrasion of the seal elastomer. The mechanical life of the valves is very high. Individual valves have already been operated in ground application for some billion cycles. During the µFCU development, a set of 30 valves with three different seal elastomer has been tested in an accelerated wear test. To increase the wear, the temperature was also cycled in a climate chamber in 6 hours from -40°C (below glas transition temperature for the used Viton) to +110°C. Additionally a flow of more than 1000 sccm has been established with a differential pressure of approx. 2 bars to maximize gas dynamic abrasion.

The test was performed with Argon and Xenon as test gases in a closed loop pumping system. After some ten million cycles the test was interrupted to measure the leakage. After 300 million cycles the valves showed first wear effects. After 350 million cycles the µFCU internal leakage requirement of 10-6 sccs GHe was exceeded by most of the valves. The test continued to investigate the mechanical life especially a potential fracture of the spring. After additional 350 million cycles (700 million cycles in total) without valve failure it has been decided to stop the test.

Using the lifetime limitation due to seal material wear under worst case conditions, the minimum cycle operational lifetime capability of µFCU can be estimated. The result is presented in Figure 5 for a 3 Hz operation.

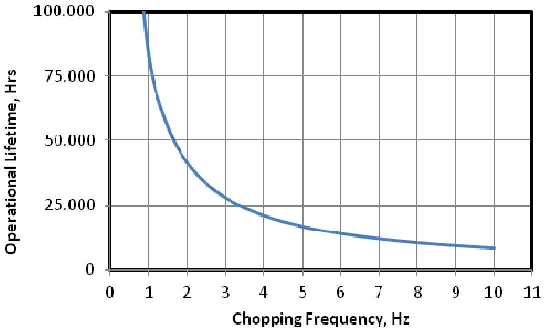

Figure 5. Estimated operational lifetime capability in dependency of the average chopping frequency

2. *Flow Path Board*

The function of the flow path board (FPB) is very similar to a PCB in electronics. They shall interconnect components, provide flow resistors and cavities and are the mechanical interface to the satellite panel.

FPBs are made of a stainless steel plate material. Microchannels are engraved into the surface. The channels interconnect holes and borings. Later the borings are the ports for surface mounted components like valves or particle filters. The individual plates are attached together to a stack. The stack is then bonded vacuum tight by a special process. The final board carries a three-dimensional network of channels and connecting ports for components.

3. *Particle Filters*

Particle filters have been designed for a surface mount interface required by the integration to the FPB. The filters are completely made of 316L stainless steel. The filter element is a woven mesh fabric with a maximum pore diameter of 5µm. The filtration grade of each filter is verified by a bubble test.

IV. System Integration Aspects

A. Venting Capability

To integrate the µFCU into a system, a pressure pre-regulator is required after the tank to reduce the inlet pressure to 1 - 3 bars (nominal 2 bars). For pre-regulation a conventional mechanical pressure reducer may be used. This type of regulator shows typically a high leakage rates and a high lock-up pressure. They need precaution measures to avoid an increased pressure in the subsequent low pressure lines. Standard solution is a pressure relief valve with a safety margin of a factor of two. For a nominal pressure of 2 bars such a valve will open at 4 bars. After release of some pressure the relief valve will close again and the residual pressure stays close to the open pressure. It is the task of a well designed FCU to open the flow lines to vent the pressure down to the nominal value. Therefore the FCU has to have the capability to open against the pressure relief valve set point plus a margin. µFCU can be operated up to 8 bars (12 bars demonstrated).

B. Self Limiting Maximum Flow

The µFCU devices has an inherent safety feature. The fluidic microchannels inside the FPB can only carry a maximum gas flow. If the flow is further increased e.g. by increasing the inlet pressure with fully opened valves the flow is choked by gas dynamics. This self limiting effect occurs at 145% of the specified full scale flow at nominal pressure. A 8 sccm flow line is limited to 11.6 sccm under worst case conditions (Figure 6).

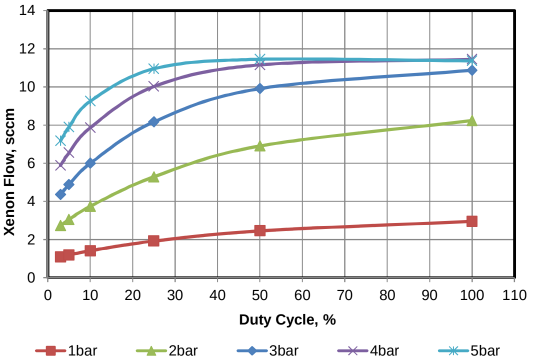

Figure 6. Self limiting maximum flow of a 8 sccm F.S. flow line (nominal 2 bars)

C. System Integration Concepts

µFCU has been designed to fit in existing electric propulsion systems without changing the overall operation concept. In a typical configuration one µFCU drives one thruster and a neutralizer. In redundant configurations like it is standard for SPT, two µFCUs would be combined. One line of each µFCU jointly supply the anode to provide a parallel redundancy. The second flow line is connected to the two neutralizer cathodes. This configuration can also be implemented for HEMPT or RIT.

Electron bombardment thrusters would use two standard µFCUs for three required flow lines. Alternative, a three or multi-line FCU could easily be developed by adding a third outlet line to the FPB. As the µFCU is a flat device with equal conditions for each line, further lines may be added as long as the maximum flow capability of the isolation valve is not exceeded.

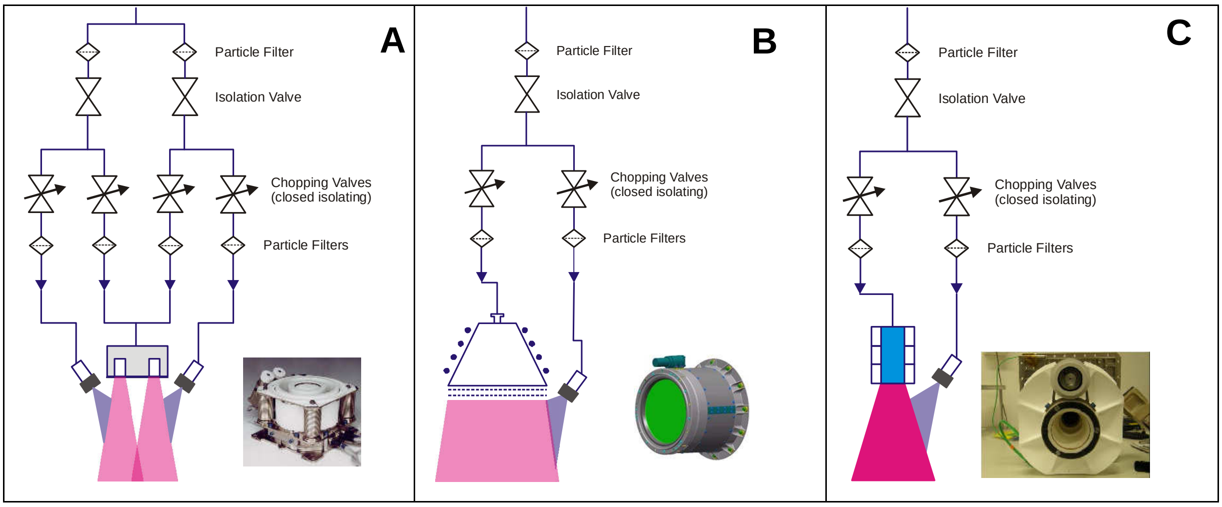

Figure 7. Integration concepts for a existing EP systems
A=SPT double redundant, B=RIT single redundant, C=HEMP single redundant

V. Key Performance Figures

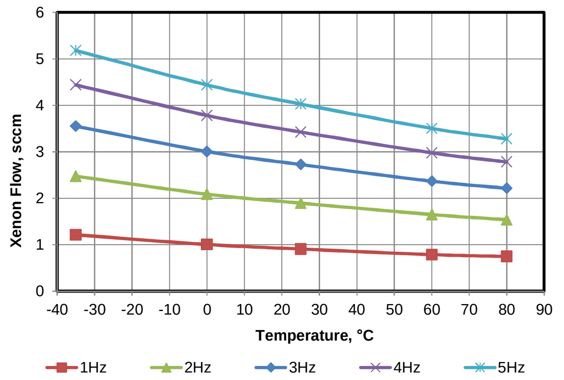

Figure 8. Temperature dependency of the transfer function in frequency modulated mode with a pulse width of 10ms at 2 bars inlet pressure.

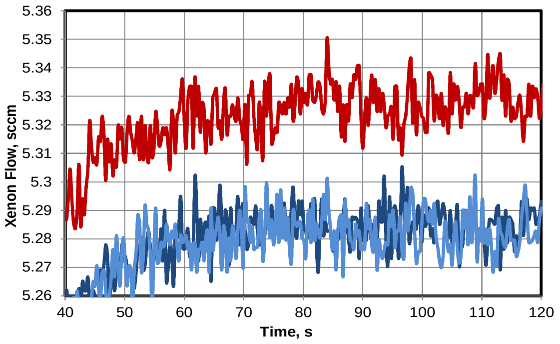

Figure 9. µFCU has an outstanding stable and repeatable operation. Lower (blue) curves are at identical environmental conditions at 3 Hz while the upper (red) curve shows the flow at 1% increased inlet pressure. The outlet flow measurement noise is about 0.5%. No flow ripple detectable.

Table 1. Operating parameters

Parameter	Value
Nominal flow range	0.1 … 1.5 sccm Xe 1 … 10 sccm Xe (other values can be realized with different internal flow channel sizes)
Self limiting by flow choking	At 145% of nominal flow range
Independent flow lines	2
Flow ripple	<1%
Op. pressure range Nom. inlet pressure	1 to 3 bars 2 bars
MEOP for venting Proof pressure	8 bars (12 bars demonstrated) 12 bars
Operational temp. Non-operational temp.	-30°C … 90°C -40°C … +110°C
Internal leakage External leakage	$<10^{-6}$ sccs GHe over lifetime cyc. $<10^{-8}$ sccs GHe over lifetime cyc.
Lifetime	> 300 mio. cycles equiv. 28 000 op. hrs @ 3 Hz
Filter	5 µm absolute in inlet and outlet flow lines

Parameter	Value
Mode of operation	pulse-width-modulation or frequency controlled
Mass Dimensions	62 grams 54 x 46 x 25 mm
Outer surface material Wetted surface material	316L, PU potting 316L, Viton
Joining Technology	All welded
Random Vibration	21.5 gRMS
Gas compatibility Fluid compatibility	He, Kr, Xe, N_2, air IPA, DI water
Power	20V...24V valve operation < 5 W full flow
Control unit	not included, to be implemented in EP system
Electric interface Fluidic interface	Flying leads, customer spec. 1/8" 316L tube
Technical readiness	TRL 5+ pre-qualified
Export restrictions	ITAR free

During the development the focus has been put on small flow ranges as they are more difficult to achieve. The main challenges are due to the size of the optimal flow channel and the control of the gas pulses. Larger flows of more than 10 sccm have already been demonstrated in the lab. In a next step µFCUs with about 50 sccm will be manufactured for coupling tests with standard thrusters.

VI. Status

The component and process development has been finished with success. Two EQMs have been built and tested in a pre-qualification program. All qualification relevant tests have been performed. EQM 01 has been tested with respect to thermal vacuum, thermal cycling and proof pressure, while EQM 02 was subject to the vibration tests. Finally EQM 02 shall also perform the thermal and pressure test.

With successful pre-qualification tests the µFCU has reached TRL-5 and covered a large portion of TRL-6 (prototype test in relevant environment).

VII. Conclusion

A new miniaturized flow xenon flow control unit has been developed and pre-qualified[1] by a project consortium led by AST Advanced Space Technologies GmbH. All relevant tests have been successfully performed to qualification levels on two engineering and qualification models. In a further campaign, started in September 2013, the tests shall be continued to perform all verifications on the same model.

The new ITAR free design allows a significant reduction in mass and size. The operational concept, the excellent open loop stability and the simple interface requirements allow an easy integration into existing electric propulsion systems.

The large potential of the used miniaturization technology has been impressively demonstrated by reducing the total mass to 62 grams for a two flow lines design. The flat design with access to all welding positions, the low complexity in operation and the relaxed requirement for the driving electronics give µFCU a great potential for system cost reduction. After reaching TRL 5 the µFCU is now ready for a formal qualification program.

Acknowledgments

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