μFCU - Results of a Prequalification Test Campaign

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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 noble gas flows. The μFCU can be adapted to different flow range requirements ranging from micropropulsion to large EP systems. Beside its small footprint (55 x 50 mm) and small weight (less than 60 g) the μFCU outperforms other concepts with respect to thermal environment, lifetime capabilities and leakage. During a prequalification test program, funded by the European Commission, the μFCU demonstrated its maturity for a formal qualification program. The prequalification tests covered all relevant requirements like vibration, thermal vacuum, lifetime, pressure proof and burst pressure tests etc. This paper gives an overview on the test results of the prequalification tests.

I. Introduction

Electric propulsion systems require 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[2,3] 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 and stringent mass budgets. Consuming such a large portion of the total system mass, the use of an EP system with actual FCUs is impractical. Even for larger satellites the mass of the electric propellant system may impact the overall system. More important for this class of spacecraft is the development of system cost. With increasing competition a pressure on cost has emerged even for new technologies like EP.


Figure 1. μFCU EQM 02 in comparison to the size of an USB stick

AST Advanced Space Technologies GmbH is a new player in the field of flow control units for electric propulsion (EP) systems. In a 22-month development project, funded by the European Commission via the 7th Framework Program, a joint team of five partners designed, manufactured and tested a new miniaturized flow control unit. During the development a lot of specific test have been conducted to verify function and performance of the individual component. A special focus has been put on manufacturing processes and on the development of measurement equipment and ground support equipment (GSE).

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After validating the components and after mastering the manufacturing processes, two engineering and qualification models of the µFCU have been built and tested. These tests cover a full qualification program but without a full lifetime test. The lifetime capability of the critical component (valve) has been investigated on component level. The FP7 project "µFCU" had a dense 22-month time schedule with parallel development activities. The EQM tests have been split in two groups, the thermal stress and pressure tests and the vibration stress tests. Each stress type has been applied to one of the EQMs in parallel.

Finally the EQM 02 (mechanical stress) will also undergo a proof pressure test and a thermal vacuum test with temperature cycling. At the end EQM 02 will have been exposed to all stress types. Goal of this "pre-qualification" process is to demonstrated that, even after such a short development time, the design is mature to enter a formal qualification.

II. Valve Component Test (Accelerated Wear Test)

During a component level test by valve's manufacturer, a number of 30 valves have been set into an accelerated wear test to probe different seal materials (3 materials) with respect to their long life capability. The wear test operated the vales under worst case conditions (even below glas transition temperature). Thermal cycles in a climate chamber (-40°C to +110°C temperature cycles every 6 hours) have been applied. Full flow of more than 1000 sccm at nominal pressure of 2 bars has been established with Argon and Xenon to simulate the maximum gasdynamic erosion. In steps of several ten million cycles the test was stopped to perform a leakage test. One of the valves of each seal material was removed from the set-up during each interruption for later analysis. The finally selected Viton elastomer seal showed first signs of degradation after more than 300 million switching cycles. After 350 million cycles the leakage exceeded the µFCU leakage requirement of 10^{-6} sccs GHe. Although the requirement was exceeded, the valves have been further operated to gain experience with respect to mechanical failures. After more than 700 million cycles the test was stopped. The mechanical life of the valves seems to be much higher. Individual valves from the industrial production had already demonstrated several billion mechanical switching cycles.

From this test, the lifetime cycle capability of the µFCU has been estimated to be at least 300 million cycles under worst case conditions.

III. Pre-Qualification Test Campaigns

A. Device-Under-Test (DUT)

Two engineering and qualification models (EQM 01 and EQM 02) have been manufactured according the processes developed and documented in the component and assembly method development phase. Both EQM have an identical design. The FCU has two flow lines with different flow ranges. The high flow port provides up to 8 sccm Xenon, the small one up to 0.5 sccm nominal full scale at 2 bar. The maximum fluidic flow is limited inherently to about 145% of the nominal flow range. The inlet and the outlet flow lines are protected by a 5µm particle filter.

EQM 01 is equipped with additional temperature sensors on top of each valve. The sensors measure the temperature of the "hot spot" of the coil assembly.

EQM 01 is depicted on Fig.2 while EQM 02 is shown on Fig.1. The µFCU is an all welded stainless steel device so that it is very robust to handle. The surfaces have been cleaned with de-ionized water and isopropyl alcohol (IPA) prior to test.

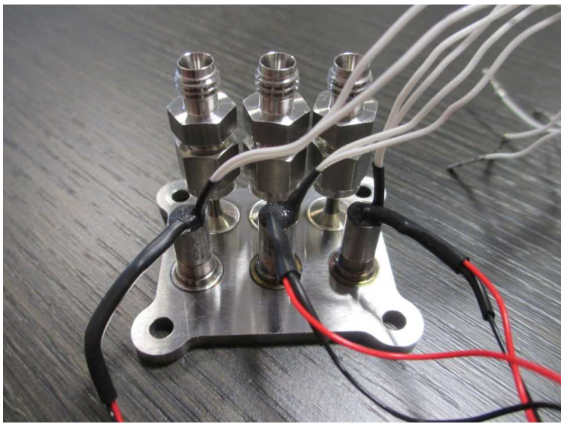

Figure 2. µFCU EQM 01 with temperature sensors (red/black cable) and 1/8" Swagelok couplings connected to the flow line ports.

Both units have been functional tested as part of the manufacturing tests. These tests are not further reported in this document.

B. Thermal Vacuum Test (EQM 01)

The thermal vacuum test has been performed at the 1st Institute of Physics at the Giessen University in the electric propulsion lab. The device under test (µFCU EQM 01) has been put onto a conductive baseplate and was covered with s shroud directly bound to the plate. The baseplate was equipped with electric heaters to warm up the set-up. For cool down the set-up was attached to a liquid nitrogen cooled cold plate. By regulating the electrical heaters it was possible to control the temperature at the device under test between -50°C and +120°C.

During the test campaign the temperature was stepped over an operational temperature range of -35°C to +80°C (EQM 2 will be tested from -40°C to +100°C). The pressure in the vacuum chamber was kept below 0.1 mbar to eliminate thermal convection effects. The first thermal cycles were dedicated to performance tests and leakage tests. After this characterization of the FCU for all temperatures the thermal cycling test has been conducted. After the cycling a second characterization has been done to identify a potential degradation. After the thermal stress the FCU was removed from the vacuum chamber to perform the pressure proof tests. After pressure proof test a final inspection and characterization was scheduled. The total procedure is given in Fig.3.

The thermal vacuum test campaign was not only used to measure the temperature dependency of the flows but also the pressure dependencies. Therefore for each temperature level the inlet pressure has been varied. For this working point the FCU was operated over the full regime, i.e. with pulse width modulation ranging from 5ms (minimum) to 100% duty cycle and with frequencies ranging from 1 Hz to 5 Hz. The large dataset has been analyzed.

1. *Result Temperature Dependency Test*

During the temperature dependency test the influence of temperature on key parameters has been investigated. These key parameters are:

- the transfer function between PWM/FM and flow (PWM test)
- the set on / set off voltages of the valves (EP Test)
- the maximum flow at opened valves
- internal leakage

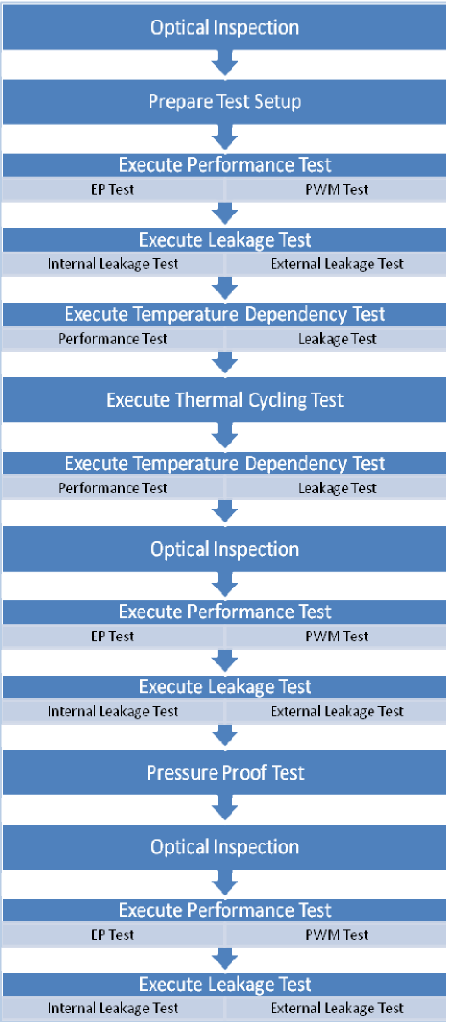

Figure 3. Test sequence of EQM 01 pre-qualification tests

The basic behavior of the flow control is depicted in Fig.4. The flow can be controlled by the chopping frequency. The transfer function is acceptable linear for an open loop device. Pulses with fixed duty cycle and increasing frequency will also increase the flow as expected. The second way to operate a µFCU is a fixed frequency and a variable pulse width. This mode is less linear but has the same overall tendency. If the pulse width is increased, the flow increases. A further positive correlation shows the inlet pressure. If the pressure is increased while the other parameters are fixed, the flow will also increase. The effect is linear for low flow rates, but at high rates the picture is changing. The maximum flow through the µFCU is limited due to a choking in the microchannels. At this point an increase of the pressure even at fully opened valves will not increase the flow anymore. The choked flow is about 145% above the full scale flow at nominal conditions (Fig.6). Figure 7 proves that the choked flow is independent of the temperature (less than 2% variation over full temperature range).

The viscosity of a gas increases with the gas temperature. As result the flow is dropping at elevated temperatures. This general behavior applies also on the flows of µFCU. For the full temperature range the nominal flow varies about +/- 25%. The effect is slightly non-linear with an increase to lower temperatures (Fig.5).

The leakage measurement shows a different temperature dependency (Fig. 12). The leakage rate increases with temperature. This can be explained by the different flow mechanism. In a leak tight valve Helium still can propagate through the seal elastomer by diffusion. Diffusion is a process that increases with the temperature (exponential behavior). The leakage rate that is not related to diffusion should be below the measured rate at low temperatures. Nevertheless leakage requirements typically refer to Helium tests, so the leakage rate of the µFCU under test was below 10^{-7} sccs GHe at room temperature and with nominal pressure of 2 bars. The curve of the leakage measurement shows a slight hysteresis. This is linked to the continuous change of temperature during the test and the long duration until the leakage value has settled.

The electro-mechanical performance of the valves has been verified by the set-on/set-off voltages. These parameters define the lowest voltage at which the valve has reliably switched to open, respectively the voltage at which the valve has reliably closed. The results are presented in Fig.10. The set-on/set-off voltages show only minor effects by the temperature. The effect is driven by the change of the coil resistance.

The performance mapping has also been used to investigate the flow stability, the settling time and the ripple of the µFCU flows. Figure 8 shows the settling time for nominal conditions (2 bars, room temperature). The step response depends on the flow level and slightly on the chopping frequency. The higher the commanded flow rate, the faster the flow settles. The settled flows do not show any signs of an outlet flow ripple. Even if the data set is analyzed with increased scaling (Fig.9) no ripple can be detected. It should be mentioned that for this data set the data acquisition sampled with 3 Hz, the same rate as the chopping frequency. Nevertheless, if a ripple is covered by the low sampling rate, it would be detectable as noise with some harmonics. The noise level is about 0.5% and no harmonics are observable.

The same diagram reveals the excellent stability of the µFCU in open loop. As long as the environmental conditions are constant, the flow and its dynamic behavior like repeatability remain constant. The sensitivity of the measurement set-up was sufficient to resolve even small variations, e.g. an inlet pressure increase of 1%.

2. *Valve Temperature*

The thermal vacuum test provides an important input for the system engineering. It gives realistic values for operation temperatures of the components in a relevant environment. The µFCU was equipped with PT-100 sensors at the tip of the valves to measure the thermal hot spot. This temperature represents the coil temperature and the temperature of the potting material. The coil wire is able to withstand 180°C. The limiting element is the polyurethane potting which is specified for a continuous temperature of +125°C.

Figure 11 shows the temperature of the potting material at the valve tip for different baseplate temperatures. It remains below +110°C at full power of +24V operation and a +80°C baseplate temperature (interface µFCU to spacecraft). Together with a large margin in the required set-on voltage compared to the test voltage of +24V it should be possible to extend the operational temperature range to +90°C or even beyond if the driving voltage is lowered. A further optimization could be a pull-in / hold operation for the isolation valve, as the isolations valve sees a 100% duty cycle while the other valves are chopped with a lower average power.

Together with the other temperatures gathered from the test a thermal model of the µFCU with its active components shall be developed in future for further optimization.

3. *Result Temperature Cycling Test*

After performing slow temperature cycles between -35°C and +80° for temperature dependency tests, the temperature cycling continued with fast cycles between -50°C and +110°C (non-operational). During the fast cycling phase no dedicated tests have been performed. The µFCU remained in the non-operational state with all valves closed.

After the cycling a further dependency test was started to identify potential changes or degradations in the µFCU performance. Together with the measurement ramps of the first dependency test and with the fast cycling a total of 14 cycles has been completed (eight non-op cycles). Figure 13 presents the transfer function between flow and duty cycle at nominal condition before and after the thermal cycling test. The measurement revealed no changes. Also the internal leakage stays within the measurement uncertainty (Fig.12). Finally after all tests also the external leakage has been verified.

As result it has been verified that the µFCU withstands the stress of a thermal vacuum and temperature cycling test without degradation.

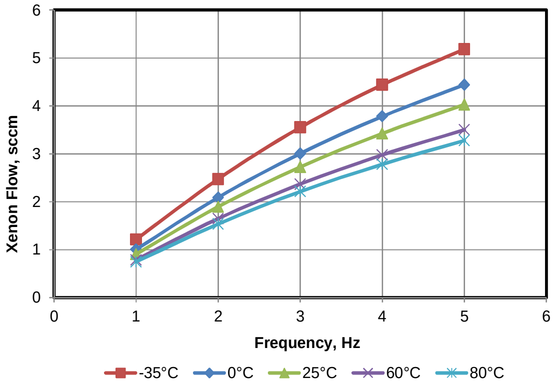

Figure 4. Flow in dependency of the chopping frequency at fixed duty cycle

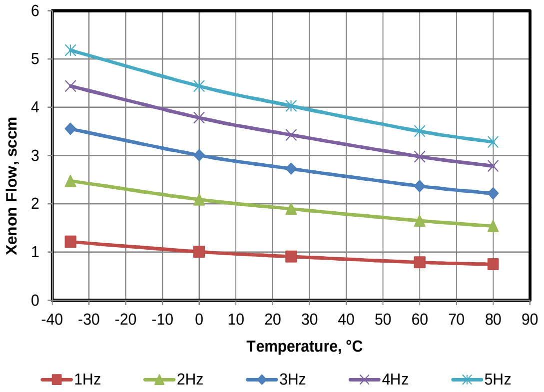

Figure 5. Influence of temperature on the transfer function between FM and flow

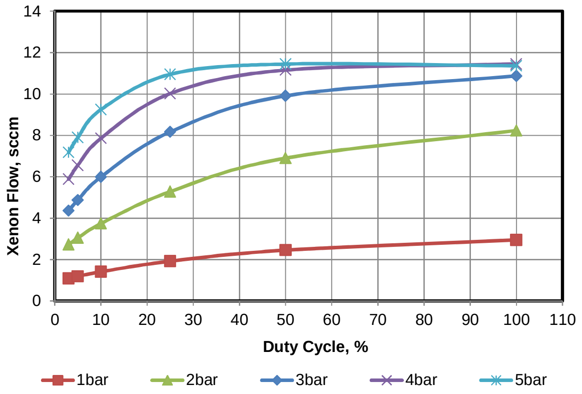

Figure 6. Self limiting effect due to choking. Even at 5 bar and 100% duty cycle the flow is limited to 11.5 sccm

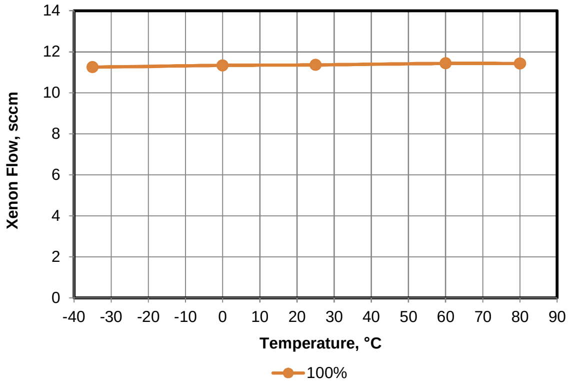

Figure 7. Temperature dependency of the choked flow (5 bars; 100% duty cycle)

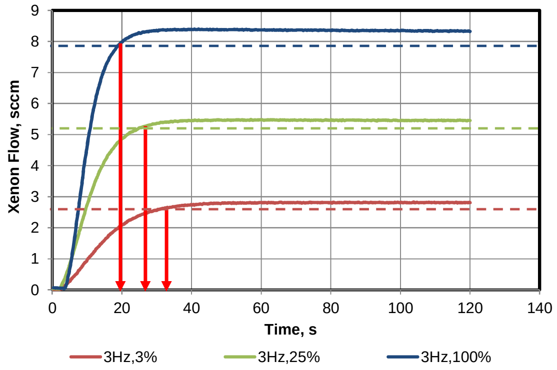

Figure 8. Settling time after commanded step at nominal conditions (95% percentile is dotted)

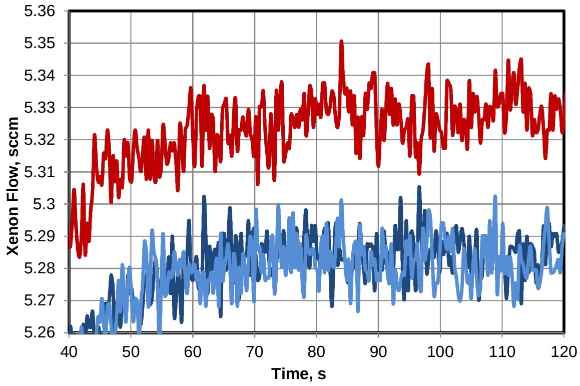

Figure 9. µFCU has an outstanding stable and repeatable operation. Lower (blue) curves are at identical environmental conditions at 3 Hz while the upper (red) curve shows the flow at 1% increased inlet pressure. The outlet flow measurement noise is about 0.5%.

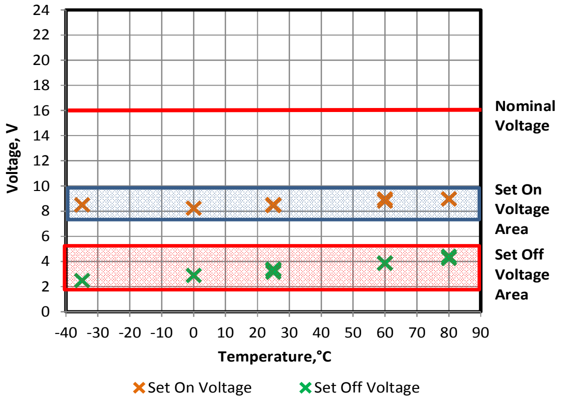

Figure 10. **Set-on/Set-off voltage in dependence of the µFCU temperature. "Nominal Voltage" defines the specified upper limit of the Set-on voltage**

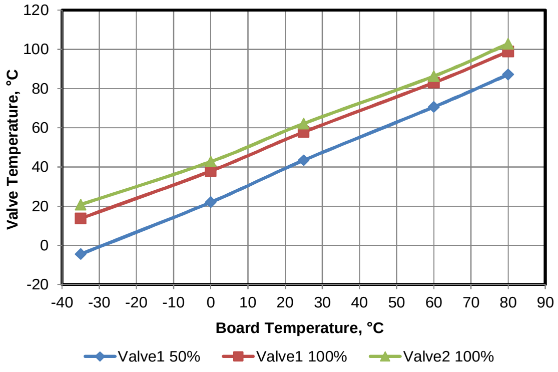

Figure 11. **Valve coil temperature in dependency of the duty cycle and the baseplate temperature**

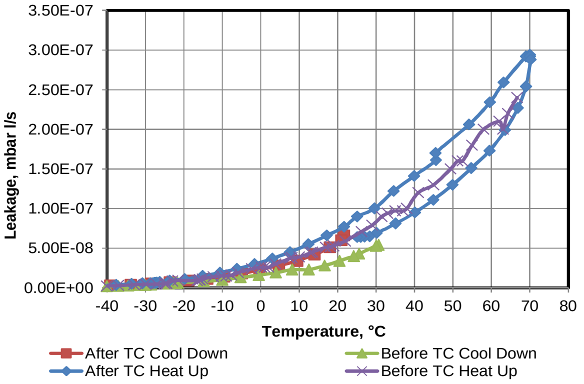

Figure 12. **Internal Helium leakage rate in dependency of the temperature (at 2 bar) before and after temperature cycling (TC) and with measurement hysteresis (ramp up/down)**

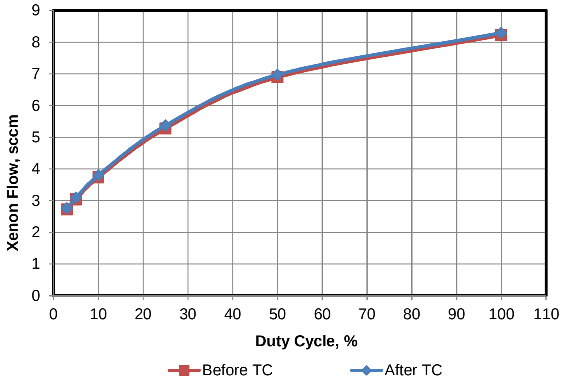

Figure 13. **Flow characteristics in pulse width modulation before and after thermal cycling test**

C. Proof Pressure Test (EQM 01)

After the thermal vacuum test the EQM 01 FCU was placed into a bath with de-ionized water for proof pressure tests. The water basin allows a detection of leakage during the tests and reduces the effects of a potential burst. First the maximum expected operational pressure (MEOP) has been tested. At this pressure of 8 bars the µFCU must be capable to open the valves to release gas (venting in case of a pressure reducer lock up or failure). The EQM 01 passed the test without problems. Second the pressure was increased to the proof pressure (12 bars). At this level the µFCU has to survive without performance degradation. The test has been conducted with closed and with open valves for three times. The dwell time of each pressure cycle was 5 minutes. The EQM 01 performed well and leakage or degradation occurred. Finally it has been demonstrated that even at 12 bars the valves can be opened (at least at room temperature).

After the proof pressure tests, the µFCU has been characterized again. All parameters were still within the specification and within the measurement uncertainties compared to the test at the beginning of test campaign. A microscopic visual inspection of the weld seams showed no irregularities.

D. Vibration Test (EQM 02)

The vibration test campaign with EQM 02 followed an equivalent scheme as the thermal test campaign on EQM 01. First the FCU was characterized by measuring all relevant parameters. Then the FCU was exposed to the vibration stress. Afterwards the parameters have been re-measured to identify potential deviations. As specialty, the vibration set-up included a leakage test during vibration. The FCU was connected to a leakage tester by flexible PTFE tubes (Fig.14). Due to the tubes, the sensitivity of the test was limited, so that the ultra low leakage could not be controlled, but it was sufficient to test the internal leakage requirement of 10^{-6} sccs GHe. The low leakages have been reconfirmed in a leakage test after the vibration test campaign.

The vibration test has been carried out for different vibration level. The direction out-of-plane has been tested in two load steps up to 21.5 gRMS (Fig.15). The perpendicular direction in-plane has been vibrated up to 17.25 gRMS. During all tests no increase in the leakage tester signal has been observed. This is a clear indication that the valves remained closed.

The internal and external leakage measurements performed before and after the vibration test confirmed the ultra leak tightness of the valves and the robustness of the welds.

Although the FP7 funded project has ended in September 2013, the tests will be continued to conduct the thermal stress test on the EQM 02. Finally all pre-qualification tests shall be applied and passed on the same piece of hardware. Two further models for high flow rates of up to 50 sccm Xenon are under manufacturing. These models are planned to be provided to electric propulsion system manufacturers for coupling tests.

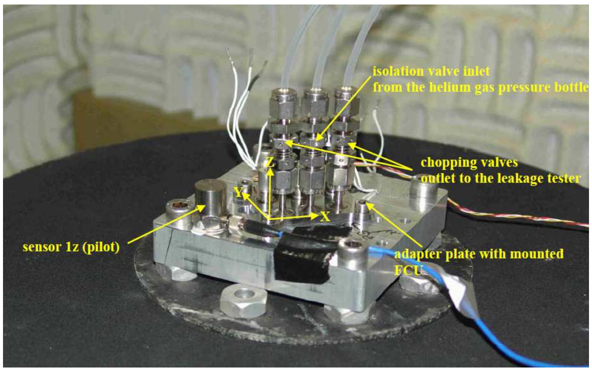

Figure 14. µFCU EQM 02 on the shaker. The PTFE tubes for leakage measurement coming from the top

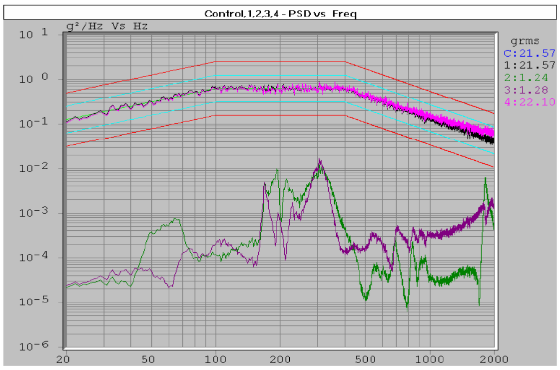

Figure 15. Random vibration test spectrum (21.5 gRMS out-of-plane)

IV. Conclusion

A new miniaturized flow xenon flow control unit has been developed and pre-qualified 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 system.

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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