# International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

## *Mechanical design and testing of the MOMA flight model laser head for the EXOMARS 2020 mission*

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# Mechanical Design and Testing of the MOMA Flight Model Laser Head for the EXOMARS 2020 Mission

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## ABSTRACT

A hermetically sealed laser head (LH) emitting laser pulses at a wavelength of 266 nm has been developed and tested for the Mars Organic Molecule Analyzer (MOMA) instrument of the ESA/Roscosmos ExoMars 2020 mission. MOMA comprises a gas chromatograph (GC) and a laser desorption mass spectrometer (LDMS). Its primary function is to search for traces of present or past signs of organic molecules in subsurface material probes. The LH is used as an excitation source for the LDMS part of MOMA. Its design fulfils stringent mass and volume requirements and is realized as a hermetically sealed system. It consists of a laser diode pumped Nd:YAG based laser oscillator, a frequency conversion stage for frequency quadrupling of the fundamental laser oscillator wavelength, a compact monitoring stage for internal laser pulse detection, a beam shaping telescope and an adjustable laser beam steering unit with the purpose of guiding the generated UV laser beam to its target position in front of the mass spectrometer (MS) ion inlet.

The system has undergone extensive functional and environmental testing including vibration, shock and thermal vacuum chamber tests. After completion of the functional and environmental test campaign, the LH has been integrated on the MOMA mass spectrometer. Here we report on the mechanical design of this LH and its environmental testing. Furthermore, the LH was successfully tested both functionally and environmentally on LDMS level.

**Keywords:** EXOMARS; MOMA; diode-pumped solid-state Laser; Thermal-vacuum test; Vibration test; Shock test; space-qualified laser; 266 nm laser

## 1. INTRODUCTION

The MOMA instrument is part of the life science instrument package onboard the ExoMars 2020 Mars lander rover. MOMA has two paths to allow the detection of signs of present or former life [1][2]. A GC built by LISA/LATMOS in France and a LDMS, consisting of a laser pump unit (LPU) built by Max Plank institute for solar system research (MPS; Germany), a laser source built by Laser Zentrum Hannover e.V. (LZH; Germany), and a MS including electronic units built by NASA, Goddard Space Flight Center (GSFC). A novelty of the MOMA instrument is its LDMS capability which has never been used in other planetary exploration instruments. It allows the detection of larger non-volatile organic molecules with molecular weight of up to 1000 u.

A UV laser source emitting nanosecond pulses with pulse energy of about 130 μJ at a wavelength of 266 nm is required for the ionization of non-volatile soil constituents. For this purpose, a rugged and light-weight passively q-switched, diode-pumped Nd:YAG laser oscillator with external frequency quadrupling has been developed, tested and integrated into the LDMS instrument. The laser is capable to be operated at environmental temperatures from -40°C to +25°C and withstand all instrument level vibrational and shock loads.

# 2. DEVELOPMENT

The optical design is described in [4] and is shown in Figure 1.
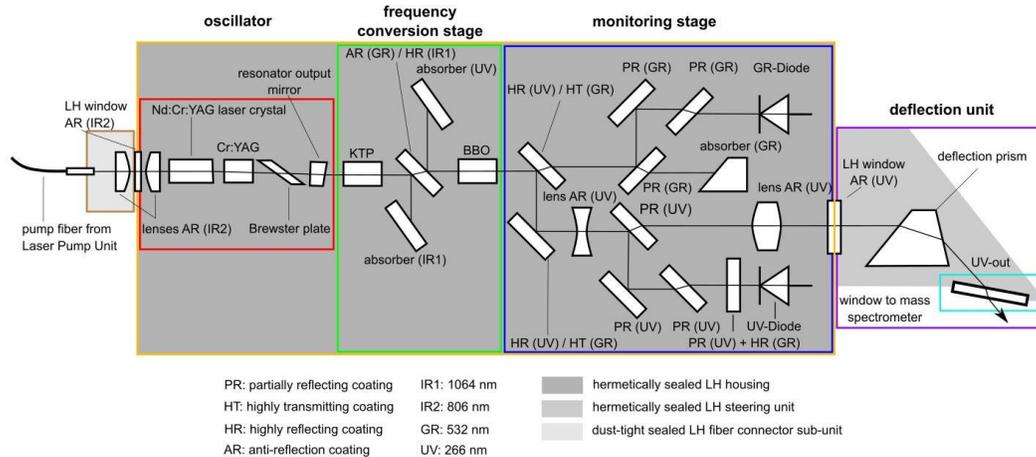


Figure 1: Optical concept of the MOMA LH consisting of four sub-assemblies: oscillator (including pump optics), frequency conversion stage (including beam cleaner), monitoring stage (including beam shaping telescope) and deflection unit. [4]

The mechanical design of the MOMA LH is separated into four main sub-assemblies, the oscillator (red in Figures 1 and 2), the frequency conversion stage (green), the monitoring stage (blue), and the sealed housing (orange) which allow to hermetical seal these sub-assemblies in a defined clean atmosphere. The pump fiber connector (brown) is attached to the laser housing. A laser beam deflection unit (magenta) deflects the UV laser beam toward the sample position beneath the MS ion inlet. This window (the so called UCZ window) (turquois) is one of the hermetic seals of the ultra-clean zone (UCZ) and acts as a seal between the enclosed volume within the beam deflection unit and the ultra-clean zone and is also the optical interface of the LH. Figure 2 shows the lower level sub-assemblies grouped as they are integrated in the LH and labelled with their mechanical degrees of freedom relevant for mounting and adjustment. The capability to align optical components and their mounts is reduced to a reasonable amount.

The assignment of the optical elements within the laser head design was driven by the optical concept, except the pump optics which is partially assigned to the sealed housing and partially to the oscillator. This has the advantage that the brazed window of the housing can be within the collimated beam path between the two pump lenses, where it has only slight impact on the optical performance (compare Figure 1 and Figure 2).
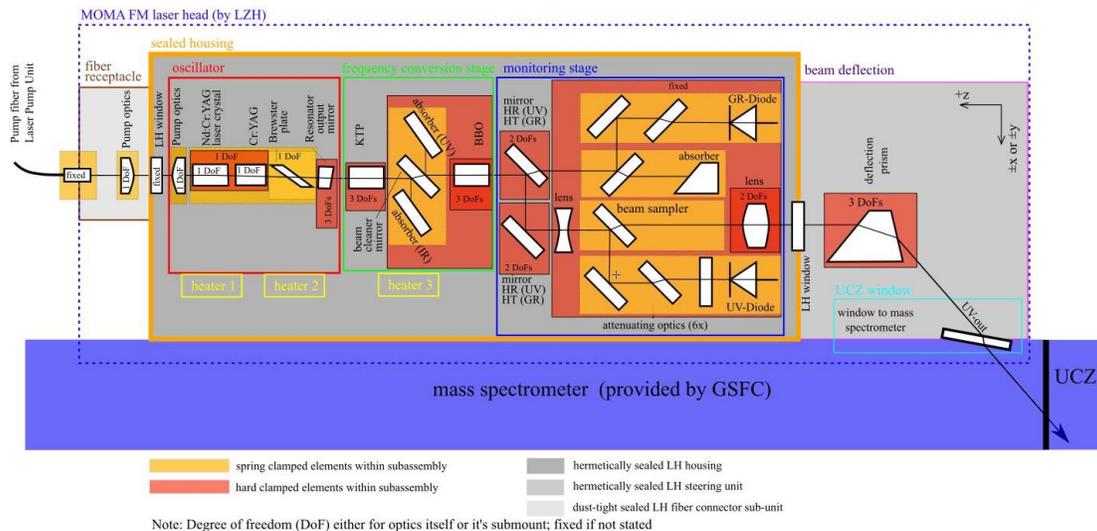


Figure 2: Mechanical concept of the MOMA LH with marked main and lower-level LH sub-assemblies and thermal hardware (H/W). All sub-assemblies are labeled with their mounting degrees of freedom (DoF), if there are any.

The MOMA FM laser head material is Titanium Grade 23 which is almost identical to the widely used Grade 5 variant, except for slightly smaller oxygen content for the Grade 23 alloy. This improves its suitability for a laser welding process applied to join individual LH housing parts.

To reduce the risk of contamination extensive cleaning and vacuum bake out procedures have been applied to the LH parts prior assembly and also in the assembly phase. The use of adhesives within the hermetically sealed LH housing is limited to a small and unavoidable amount needed for screw securing. Organic materials within the sealed housing are only used in cases without non-organic alternatives, e.g. Kapton foil heater, cable isolation and insulators needed for the internal photo diode mounting. All optical components are integrated and fixed with miniaturized clamping mechanisms.

### 2.1 Pump fiber receptacle

The SMA pump fiber connector used for early prototype models is replaced by a custom made connector based on Diamond's MINI-AVIM fiber connector design (brown in Figure 2). This custom made MINI-AVIM pump fiber connector includes the pump optic collimation lens.

### 2.2 Oscillator

The oscillator sub-assembly contains all optical components beginning with the focus lens up to the output coupler of the resonator and further parts and components needed for temperature stabilization and mounting. The focus lens is mounted identically to the collimation lens, but is kept under ambient pressure, since it is within the sealed part of the housing. The following resonator consists of three sub-assemblies. The first sub-assembly contains the laser crystal and the passive q-switch mounted together in spring loaded slotted grips. Basically this approach was used since the prototype model, improved only by clamping the optical components via their barrel surfaces thus avoiding a mechanical contact to the optical surfaces.

The second sub-assembly within the oscillator is the Brewster window, which is axially clamped, with its mounting mechanics. This sub-assembly needs to be aligned rotationally in respect to the first oscillator sub-assembly to optimize losses within the resonator.

Both previous sub-assemblies are located within an additional tube. This is mounted axially spring loaded and fixed by the third sub-assembly, the output coupler mount, which contains the resonator output coupler and is adjustable with three rotational degrees of freedom prior final fixation. All three axes need to be alignable to optimize resonator performance.

### 2.3 Frequency conversion stage

Within the frequency conversion stage, two non-linear crystals – KTP and BBO – are mounted for frequency quadrupling in the same way as the output coupler. Both crystals can be aligned rotationally in three axes – as the output coupler – to achieve optimum phase matching and conversion efficiency of these crystals.

Due to risk mitigation reasons and simplification of coatings used on following optics, a beam cleaner mirror together with two optical absorbers are placed between both non-linear crystals to filter out unconverted IR light. Also the very small portion of UV light that is back reflected from the second conversion crystal is dumped into an absorber by this mirror. Main design driver here is the available space for the three Ø4 mm optical elements. They are integrated in an enveloping cylinder with Ø13 mm diameter and a length of 5 mm, limited by the thermal hardware which surrounds the optical elements of the frequency conversion stage. The BBO crystal is integrated as close as possible to the oscillator and KTP to achieve high conversion efficiency.

### 2.4 Monitoring stage

The monitoring stage has multiple purposes. Its main function is to measure the laser pulse energy with two integrated photodiodes. Portions of both the out-coupled 266 nm laser beam and the internally dumped 532 nm laser beam are measured with separated photodiodes. The monitoring stage acts also as a beam dump for the frequency doubled 532 nm laser light. Beam shaping lenses are integrated in the monitoring stage to increase the beam size on the coated exit window and to focus the UV laser beam onto the sample beneath the mass spectrometer ion inlet within the ultra-clean zone where Martian soil samples are presented to the MOMA instrument.

The separation of the frequency doubled and frequency quadrupled wavelengths is realized by two mirrors, highly reflective for 266 nm wavelength and highly transmissive for 532 nm wavelength. Both mirrors are mounted individually

within a mount with 2 degrees of freedom for each mirror (one lateral, one rotational). With these alignment possibilities the beam can be alignment towards the nominal center of the second integrated lens. This lens has two lateral DoFs to pre-align the out-coupled laser beam towards the design target position.

## 2.5  Sealed housing

The design of the sealed housing combines vacuum brazing of sapphire windows to titanium frames and laser welding of the titanium structural elements. Only due to welding process needs, a metal coated sealing ring was needed for the last welding step of the final laser, to keep particles produced by welding out of the inside of the laser head, and to reduce a possible impact from process gases to the dew point within the laser head. All brazed and welded joints were X-ray scanned and rated in means of inclusions (bubbles) and grooving. Additionally, both housing parts were leak tested individually and had a sum leak rate below $10^{-9}$ mbar·l/s.

The finally assembled laser head encloses three volumes (compare Figure 3), with individual requirements regarding leak rate and time of final closeout (see Table 1).
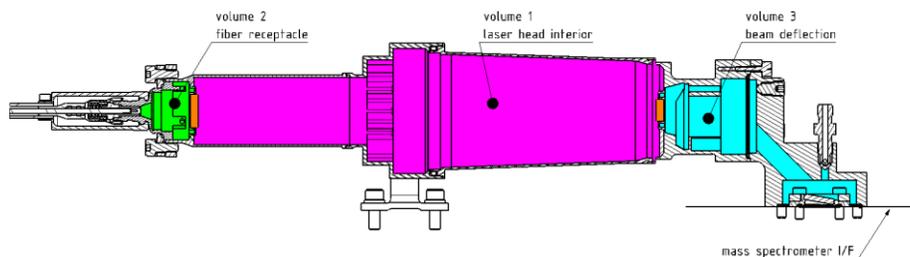


Figure 3: Cross-section through the MOMA laser head, highlighting the enclosed gas volumes; in green the receptacle volume; in magenta the main LH volume and in turquois the beam deflection unit volume

Table 1: Enclosed gas volumes within the MOMA laser head

| Vol.-No. | Name | Time of final closeout | BOL pressure in mbar | EOL minimum pressure in mbar | Required leak rate (incl. MoS) in mbar*l/s | Achieved leak rate in mbar*l/s |
|---|---|---|---|---|---|---|
| 1 | Main LH body | as last assembly step at LZH | 1000 | 100 | <1E-6 | <1E-9 |
| 2 | Fiber receptacle | during integration of mass spectrometer to ALD at prime contractor | 1000 | 0 | >1E-5 | >1E-3 (tested prior assembly) |
| 3 | Beam deflection unit | during integration to mass spectrometer | 1080 | 100 | <1E-7 | <1E-11[*1] <2E-8[*2] |

[*1] for 4 of 6 seals (below detection limit for other 2, tested in sniffing mode)
[*2] UCZ window

## 2.6  Prism

Most challenging in the design was the need to have an optical element that can align the outgoing beam with respect to the target beneath the ion inlet of the mass spectrometer and have this optics in a hermetically sealed volume in the end. The final design uses springs for clamping a prism, and also uses this spring load against three screws that can be accessed from outside for prism aligning through small bore holes, which can be closed after alignment. The prism itself is an uncoated fused silica substrate, cut in a way, that both optical surfaces are used close to Brewster angle, and are deflecting the beam by 44° towards the target.

## 2.7  UCZ window

The so called UCZ window closes the ultra-clean zone hermetically towards the laser. It is designed as an uncoated fused silica substrate mounted under Brewster angle in respect to the laser beam. The UCZ window integration is realized by gluing it with very low outgassing glue in a frame structure made of Invar 32.5.

### 2.8  Thermal

The MOMA LH temperature stabilization concept is realized as heat-only temperature stabilization. A heat-and-cool stabilization concept would result in a significantly more complex design.  In early prototype models only one heater was integrated inside the LH within the frequency conversion stage. With the highly temperature sensitive non-linear crystals, it is mandatory to keep the temperature stable.  During the prototype model phase, it turned out that the influence of the FCS temperature stabilization cannot be neglected for the stable operation of the oscillator. The influence is quite slow depends on environmental temperature. To improve the unwanted coupling between both sub-assemblies, later models are realized with two additional independent heaters on the oscillator to reach the set temperature fast and to reduce the dependency from the frequency conversion stage and environmental conditions [3].

For the FM LH, each of the three heaters consists of a custom-made Kapton foil heater (manufacturer: Minco), and a AD590 temperature transducer from Intersil, both space-qualified. These are powered and controlled by the LPU. The heater foils are mechanically clamped to the barrel surface of the oscillator and the frequency conversion sub-mounts; the temperature transducers are glued close to the corresponding heater.

Thermal insulations are implemented between frequency conversion stage and oscillator and within the sealed housing and mounting towards the mass spectrometer. Between oscillator and frequency conversion a thin-walled titanium cone was implemented, in order to enable the independent control of these items. The mounting, thermally low-conductive spacers are used on one side (left mounting I/F in Figure 4), which are also used to shim height deviations between LH and MS. Towards the right I/F, the titanium housing itself acts as thermal insulation (compare Figure 4).
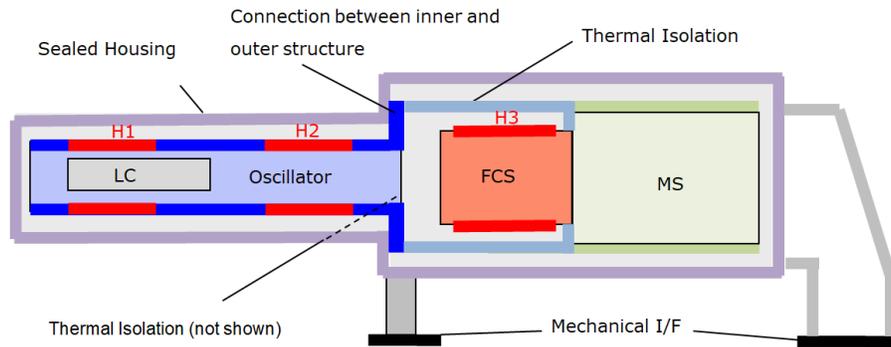


Figure 4: Thermal concept of the laser head with the three heaters (H1 to H3) clamped to the oscillator and the frequency conversion stage (FCS). The laser crystal (LC) is shown as additional heat source and the monitoring stage (MS)

### 2.9  Metrology

The mass requirement given for the MOMA laser head was not to exceed 270 g including 20% margin for the whole laser head, which is without margin 225 g. From design the predicted laser head mass were 221 g, and the measured value during metrology testing was 217 g net weight. In dimension, the LH does not exceed 44.5 mm by 56.2 mm by 218.8 mm including a MPS-provided bend-protection for the optical fiber. Metrology testing on the flight model showed that all interfaces are within required tolerances for integration (compare Figure 5).
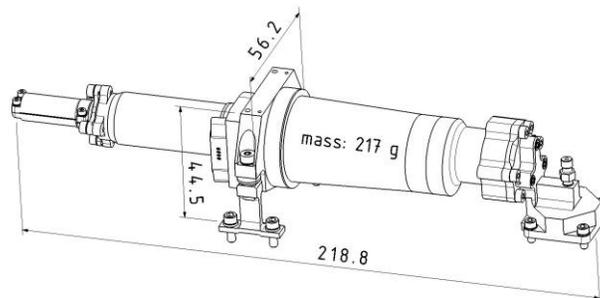


Figure 5: 3D view on MOMA LH with metrology values shown

# 3. ENVIROMENTAL TESTING

The LH was fully environmentally tested prior delivery and integration to the instrument. This includes vibration, shock and thermal vacuum testing. These tests were performed at the MPS. There, all operational tests with the laser head were run on a testbed that mimics the distances within the instrument and had a fluorescence target at the sample location. For these tests the internal housekeeping values are recorded and energy and pointing of the outgoing beam were externally measured. The sequence of tests is shown in Figure 6.
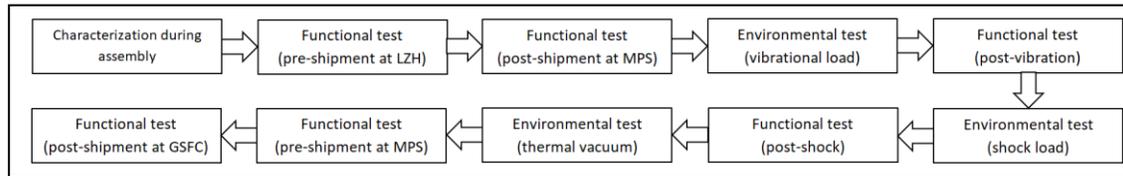


Figure 6: Environmental test campaign sequence on component level.

## 3.1  Functional tests

Since all other wavelengths are separated from the 266 nm radiation and dumped inside the LH, the UV output energy is the main characteristic of the performance of the oscillator in combination with the frequency conversion stage.

The detection of the pulse release time (PRT) as an intrinsic property of the oscillator helps to relate any changes of the UV output energy to a misalignment of the oscillator (leads also to a change of the PRT) or the frequency conversion stage components (PRT remains unchanged).

For the pointing measurement a bore in the reference block in front of the fluorescence target with a known distance of its center point to the target position was taken as a reference especially during the TVAC test to compensate for any movement of the reference block relative to the camera. The laser itself was rigidly mounted onto the reference block (as in the final FM configuration). The center point of this bore was visually determined via the adjustment of a circular aperture and compared to the position of the beam centroid (Gaussian beam profile fitted to the real shape). The absolute beam position with respect to the target value was not important during this test campaign because it can be aligned when the laser is finally mounted on the MS.

## 3.2  Vibration test

For vibrational testing, the laser head was mounted on a structural test unit (STU) of the MS instrument provided by GSFC (see Figure 7 (right)). This was done because the load requirement (shown in Figure 7 (left)) was only given to the instrument and not to its sub-components.
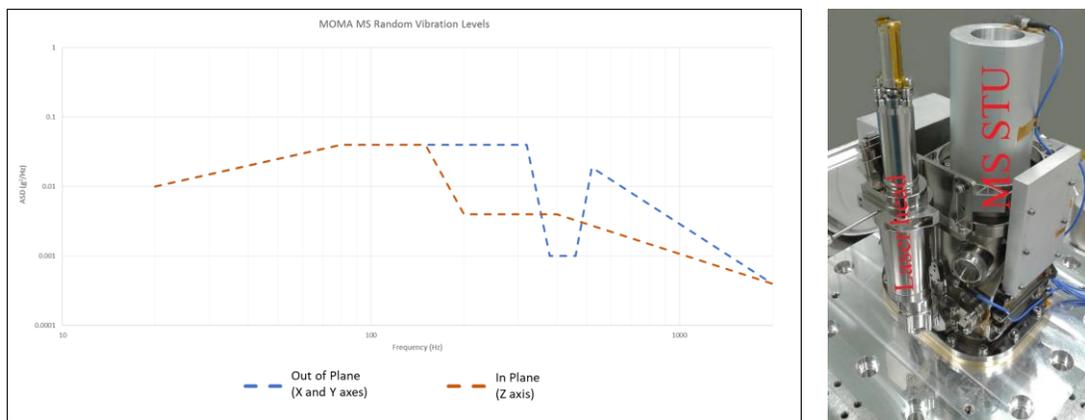


Figure 7: (left) Vibration load requirements to the MOMA Instrument at its mounting interface towards the ultra-clean-zone (UCZ) for in plane and out of plane acceleration; (right) Flight model of MOMA Laser head mounted on MS STU for vibration test

Notching was implemented to the control (compare Figure 7 (left)) and response limiting to the Wide Range Pump (WRP) mounting interface and the top of the WRP sensors in order to limit WRP responses to known allowable values.

Response channels along with a corresponding max g²/Hz response (in the form of a "limit") were to be patched into to the control loop so that the controller was able to adjust the input to prevent testing beyond WRP maximum response limits.

All three axes were tested, with resonance search before and after; loads were applied with reduced level and increased in steps (-12 dB; -6 dB; -3 dB and 0 dB). Besides other sensors, the most relevant three axes sensor was mounted on top of the center part of the LH.

### 3.3  Shock test

The shock test was done on a shock test table at Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR) Bremen.

The shock profile was calibrated with the STU including LH mass mock-up. The calibrated shock level was then applied to the X-axis of the MS STU with the FM laser head. The nominal spectrum to which the STU with the FM LH was exposed is shown in Figure 8.
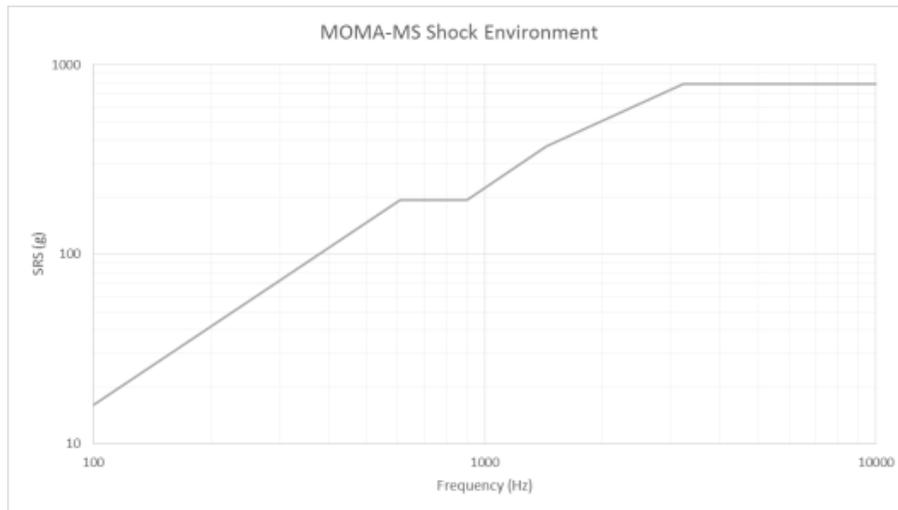


Figure 8: Input load; acceleration plotted versus frequency

### 3.4    Thermal-vacuum test

Thermal vacuum testing of MOMA LH was carried out at MPS under Martian atmosphere. For this, the laser head was mounted onto its reference block as it was for all previous functional tests. Main difference here was that the beam deflection volume was purged and needed to be hermetically sealed, due to the fact that condensation at low temperature had to be avoided to prevent damage to optics when firing the laser head.

In total five thermal cycles were performed with the flight model of the MOMA laser, which includes besides the laser head also the laser pump module built by MPS. The first and last cycle were extended to non-op limits, while the three intermediate cycles were to operational temperatures (compare Figure 9).

In addition to the functional characterization of the FM-LH before and after the thermal-vacuum (TV) test the relevant laser parameters were also checked at the minimum (-45°C) and maximum (+25°C) operational temperatures as well as at two temperatures on the rising edge of an operational temperature ramp (-20°C and 0°C). The behavior at low and high bus voltage (26V and 29.4V instead of 28V as nominal value) was also determined within a full operational cycle. Besides internally logged parameters, either pulse energy (marked as "E") or pointing (marked as "P") was also measured outside of the thermal-vacuum chamber (compare Figure 9).
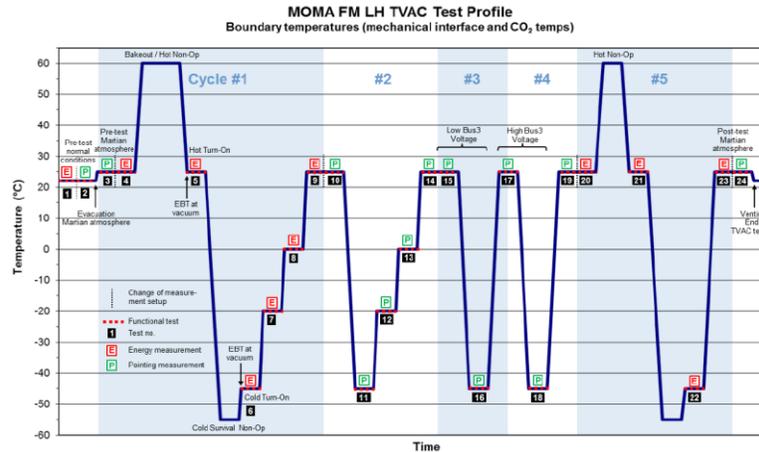
Figure 9: Temperature profile used during thermal vacuum testing the MOMA laser head; five cycles were applied with two cycles up to non-operation temperature. In red boxed "E" states externally measured energy and green boxed "P" pointing measurements

## 3.5  Environmental tests results

The UV output energy and the energy tuning behavior did not change significantly change after transport, vibrational and shock load. Only during the TVAC test a slight irreversible drift of the complete energy tuning curve towards higher FCS temperatures was observed.

Besides expected effects on the pointing (e.g. from dn/dT refractive index change within the prism), two further effects were discovered. Firstly the beam position on the target in Y direction changed slightly over almost all tests; this could be identified to be due to a mechanical effect of the prism mount, which could later be avoided by a change of the handling procedure. Secondly, the measurement data indicated that the volume of the beam deflection unit was not leak tight. However this could be solved by a change in the handling procedure. Both effects did not occur again in the thermal-vacuum test campaign for the complete MOMA instrument.

# 4.  INTEGRATION

The MOMA laser head integration was done in collaboration between GSFC and LZH within GSFC facilities in Washington D.C. in August 2017. The MOMA mass spectrometer instrument was built by GSFC within a support structure that mimics the later analytic lab drawer (ALD) and allows all components to be in their relative position to each other. This is also used as transport structure to TAS-I for integration to the ALD. All work activities at the mass spectrometer flight hardware were carried out under IS0 5 cleanroom condition. Before integration of the MOMA laser head, the UCZ window was mounted by GSFC.

At final alignment of the laser beam, a slightly different handling strategy was used to avoid the pointing trend observed during test campaign of the laser head on component level at MPS. Later environmental tests on instrument level done by GSFC proved this change to be effective. After alignment, the beam deflection unit (compare Figure 3) was leak tested once, purged with dry synthetic air (with 1% helium content) and closed hermetically afterwards. Leak tightness was confirmed again by helium sniffing from outside.

Figure 10 (right) shows the LH after final integration, first tests and screw staking with the mass spectrometer behind and the PUCZ below it within GSFC's assembly and transportation structure.
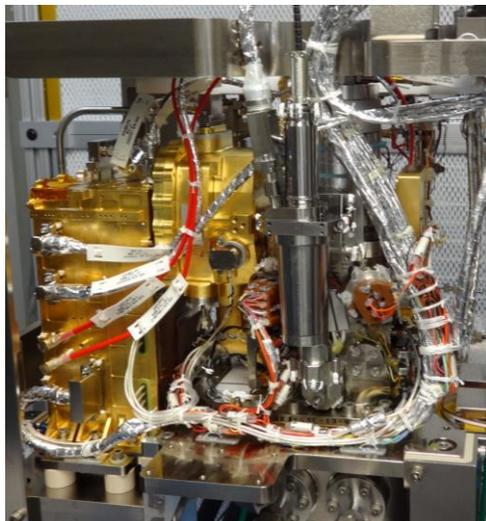
Figure 10: Fully integrated LH on mass spectrometer at GSFC clean room facility

The MOMA science team at GSFC ran first laser desorption test on targets within the PUCZ and GSFC accepted the flight laser head and the integration as successful finished.

## 5.  SUMMARY

For the EXOMARS mission, the flight model laser head was developed, assembled, environmentally tested and integrated as important contribution to the MOMA instrument for analysis of organic molecules on Mars. The LH is very robust for it low mass of less than 220 grams and delivers the required tuneable pulse energy from 13 to 130 µJ with a pulse length of 1.3 ns at a wavelength of 266 nm and will be the first laser at this wavelength in space.

Further than mentioned here, the fully integrated instrument passed the environmental testing at GSFC including LDMS runs under thermal conditions like on Mars. The next milestone will be the integration into the ALD at Thales-Alenia Space Italy in Turin and further integration into the EXOMARS rover.

## 6.  ACKNOWLEDGEMENT

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