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Optomechanical design of a 150 mJ single frequency UV laser for the AEOLUS-2 mission

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ABSTRACT

As part of the European Space Agency's AEOLUS mission, the global wind distribution in the atmosphere is currently being measured with a satellite based Doppler lidar. For the AEOLUS-2 mission, a more powerful laser is required which can emit single frequency pulses of 150 mJ energy at a pulse repetition rate of 50 Hz and a wavelength of 355 nm. Fraunhofer ILT is currently developing an engineering model of the laser beam source in cooperation with Airbus Defense and Space Germany. The work on the laser housing and heat removal system is performed by Airbus whereas the work on the laser opto-mechanical assembly is performed by ILT.

This work is based on the results of previous projects and focuses on maximizing the use of heritage: The required optical parameters in the infrared have been validated by means of a breadboard demonstrator within the NIRLI project and the optomechanical platform suitable for AEOLUS-2 has been developed in the frame of the OPTOMECH, FULAS and MERLIN projects.

For the engineering model presented in this article the proven optical design supplemented by a frequency tripling unit is transferred to the proven and to a large extent space qualified optomechanical platform with an adapted heat removal system. The design is ready, pending the detailed review.

Keywords: laser, LIDAR, wind, space, optics, optomechanics, INNOSLAB, AEOLUS

1. INTRODUCTION

As part of the European Space Agency's (ESA) AEOLUS mission, the global wind distribution in the atmosphere is currently being measured with a satellite-based Doppler lidar. For the AEOLUS-2 mission, a more powerful laser is required. Goal of the study presented in this article is to design and set up an engineering model (EM) of the AEOLUS-2 laser transmitter assembly (LTA) to demonstrate the feasibility of our optical and optomechanical concept for the AEOLUS-2 mission. The preliminary requirements issued by ESA specify a laser beam source comprising a single frequency pulsed oscillator in the Nd:YAG fundamental harmonic with subsequent amplifier(s) and a frequency tripling unit with built-in thermal stabilization of the laser frequency (Table 1).

Table 1 Preliminary requirements for the AEOLUS-2 LTA released by ESA.

Pulse energy	≥ 150 mJ begin of life, ≥ 120 mJ end of life
Pulse repetition frequency	≥ 50 Hz
Polarization	Linear, impurity < 0.5 %
Laser beam diameter	> 9 mm and < 15 mm *

Laser beam divergence	> 65 µrad and < 90 µrad *
UV fluence at laser output	< 0.5 J/cm^2
UV fluence inside laser housing	< 1.3 J/cm^2
Wavelength	One third of Nd:YAG fundamental harmonic (~355 nm)
Spectral bandwidth	< 75 MHz
Mission duration	> 5 years (goal 7 years)
* leading to a beam propagation factor M^2 = 1.3..3	

In addition to the aforementioned requirements the teams involved in AEOLUS have derived some lessons learned from the present AEOLUS mission and prior development. These lessons learned concerning the laser transmitter are amongst others:

1. Remove units with high heat dissipation away from alignment sensitive components
2. Mount as iso-static as possible
3. Keep power units away from optical bench
4. Avoid organic materials as much as possible to prevent laser induced contamination (LIC) and laser induced damage (LID)
5. Operate laser under pressure with a decent amount of oxygen to avoid LIC and LID

The Fraunhofer Institut für Lasertechnik (ILT) together with Airbus Defense and Space Germany (Airbus) have been involved in several projects for developing or improving airborne and spaceborne lasers in the last 15 years. In these heritage projects most of these requirements have already been met and the lessons learned have been implemented. This accounts especially for the optical design to generate Nd:YAG fundamental wavelength pulses with sufficient pulse energy, pulse duration and beam quality for UV pulse energy > 150 mJ at 50 Hz pulse repetition frequency (PRF) and a space qualified optomechanical design. Hence the existing optical and optomechanical architecture can be used for designing and integrating the AEOLUS-2 LTA EM.

The optical and optomechanical concepts that have been developed in the last 15 years are described in chapter 2. The heritage projects and the relevant results are listed in chapter 3. The design status of our AEOLUS-2 LTA EM is described in chapter 4

2. LASER CONCEPT

2.1 Optics

Due to the preliminary requirements released by ESA the laser system shall comprise an oscillator to generate single frequency pulses in the Nd:YAG fundamental harmonics with subsequent amplifiers and a frequency tripling unit. To assure the aspired long lifetime the UV fluence should be kept below 1 J/cm^2, hence we assume a comparably low conversion efficiency of 30 % - 35 %. For the required output pulse energy of > 150 mJ in the UV the available pulse energy in the fundamental harmonic should then be in the range of 430 mJ – 500 mJ. In a first approximation the beam diffraction factor is preserved during the conversion process, hence the beam quality in the infrared needs to be in the range M^2 = 1.3..3 as well. These parameters have been demonstrated within the NIRLI project (section 3.3). The laser comprises a single frequency seeded electrooptically q-switched and end-pumped Nd:YAG oscillator in rod geometry and two subsequent INNOSLAB amplifier stages. The oscillator's resonator length is actively controlled for frequency locking to the reference seeder. All stages are optically isolated from each other to prevent parasitic lasing. For AEOLUS-2 this concept is supplemented by the frequency tripling stage which is optically isolated from the MOPA as well. The complete optical architecture is depicted in Figure 1.

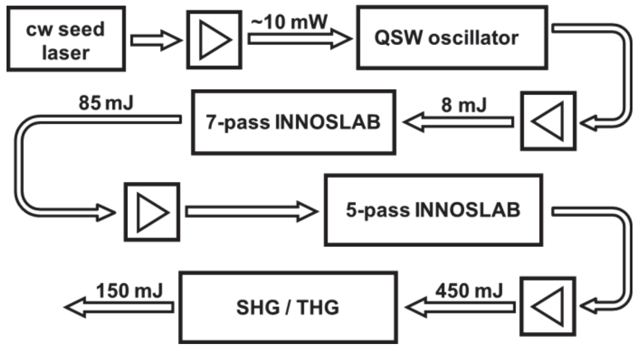

Figure 1. Optical architecture of the AEOLUS-2 LTA EM. The stages are separated by Faraday isolators to prevent parasitic lasing.

This optical concept has been tested and verified in various projects without any significant changes (chapter 3), showing excellent results in terms of optical properties and thermomechanical stability, the latter mainly owing to the INNOSLAB approach. The overall optical concept is justified as follows:

Nd:YAG is the first choice for the active medium, although Nd:YVO_4 with its by 2.4 times larger stimulated emission cross section addresses the same wavelength. But Nd:YAG has more favorable thermal properties, offers a high LID threshold, is not birefringent and is available in high optical quality.[1]

The oscillator determines most of the spectral and temporal properties of the laser radiation. The pulse length of a q-switched oscillator with a stable resonator depends on the resonator length, the gain and the output coupling ratio. To meet the spectral bandwidth requirement a minimum pulse length determined by the time-bandwidth-limit is required. For stable pulsed single frequency operation, the oscillator needs to be seeded by a stabilized reference laser and the resonator length needs to be actively controlled. To meet the beam quality requirement the resonator should be designed for diffraction limited operation which also facilitates controlling the beam and the transversal intensity distribution on the following beam propagation path.

Given the requirements an electro-optically q-switched oscillator with the end-pumped Nd:YAG crystal in rod geometry is the first choice for this application. The end-pumping allows for matching the gain volume to the fundamental resonator mode, hence enabling efficient laser operation in fundamental transversal mode with no need for resonator internal apertures. The design goals of the oscillator have been maximum pulse energy with an acceptable peak fluence on all optical surfaces, a pulse length long enough to meet the bandwidth requirement (taking into account the expected pulse shortening in the amplification and frequency conversion stages) and diffraction limited beam quality. Longitudinal single frequency operation is ensured by seeding the oscillator through the thin film polarizer, the end mirror is mounted on a piezo actuator for locking the resonator length to the reference frequency and a twisted mode configuration to avoid spatial hole burning in the Nd:YAG crystal.[2] The oscillator (scheme depicted in Figure 2) has been designed and set up in previous projects (see section 3) with the PRF of 100 Hz being the only difference to the oscillator needed for AEOLUS-2 (50 Hz).

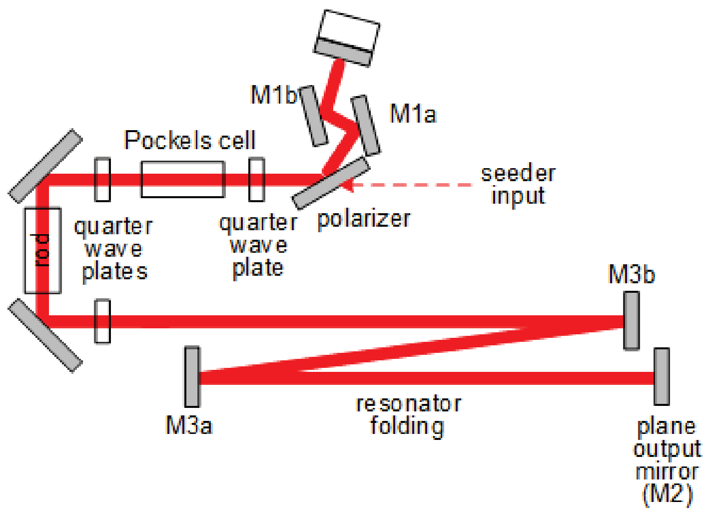

Figure 2. Scheme of the oscillator. The folding mirrors M3a and M3b are necessary for a compact setup with little footprint, the mirrors M1a and M1b facilitate the assembly and integration process. The quarter wave plate between polarizer and Pockels cell is mandatory for active high q-switching.

The first design goal for the amplifier stages has been the capability of extracting ~500 mJ pulse energy with an input energy of ~8 mJ at low fluence levels. The temporal and spatial beam properties of the oscillator need to be preserved as good as possible. To minimize the power consumption of the entire system the efficiency should be as high as possible which can be achieved by matching the gain volume to the laser mode. The saturation fluence of Nd:YAG is 0.66 J/cm^2, hence a peak fluence of ~3 J/cm^2 (corresponding to 1.5 J/cm^2 average fluence for a Gaussian beam) in the amplifier stages is a good compromise between efficient energy extraction and margin to LID thresholds. The diameter of a circular Gaussian beam at a peak fluence of 3 J/cm^2 is ~6.5 mm.

Common solid state amplifier concepts are fiber, rod, slab (INNOSLAB or ZIGZAG), or disk (thin or thick). Fibers are in general not suited here due to the required high pulse energy. Side pumped rods suited for multi-100 mJ operation are thermally inconvenient due to their surface/volume ratio, in addition to that the thermal lens is not ideal and can add aberrations and phase front errors to the beam and matching the beam parameters to the gain profile is hardly possible. Those problems are much smaller in end pumped rods, but many rods would be necessary for extracting 500 mJ of energy. Disks have the huge advantage of a good heat removal and large spot sizes which allow for keeping the fluence low. However, their thickness is significantly smaller than the absorption length and the gain is very small, hence both signal beam and pump beam have to be folded through the gain medium many times which leads to complex and voluminous mirror/optomechanical assemblies. The slab geometry provides a sufficient surface/volume ratio for good heat removal. The disadvantage of the ZIGZAG is the reduced mode matching of the pumped volume to the input beam, comparable to a side pumped rod configuration, hence the efficiency is comparably low. In contrast, the chosen end-pumped INNOSLAB concept is even characterized by a good matching of the pumped volume to the input beam. As a conclusion the authors are convinced that given the requirements for efficient frequency conversion in terms of spatial and temporal properties of the laser beam the INNOSLAB is the best choice for the amplifier concept for the AEOLUS-2 LTA.

The INNOSLAB amplifier principle is in detail described in [3]. The slab crystal is partially end pumped with high power diode laser stacks. Their beam quality is significantly lower in the slow-axis direction compared to the fast-axis direction. Therefore, the fast-axis is commonly focused to a plane located close to the entrance surface of the slab crystal to be pumped (focal plane), while the slow-axis is homogenized to achieve a top-hat intensity distribution which is typically 10 to 100 times wider than the Gaussian fast-axis intensity distribution. By the top-hat distribution in the slow-axis direction a temperature gradient inside the crystal in this direction is avoided. In addition, the homogenization reduces negative effects of degradation of single emitters or bars to the gain profile and thereby increases the reliability of the overall system. The homogenization is done by a light mixing duct. Hence the gain profile has a top-hat distribution over the full width of the optical facets (horizontal direction or slow direction) and a nearly gaussian distribution in the vertical or fast direction.

The height of the pump profile can be adapted with the focusing optics.

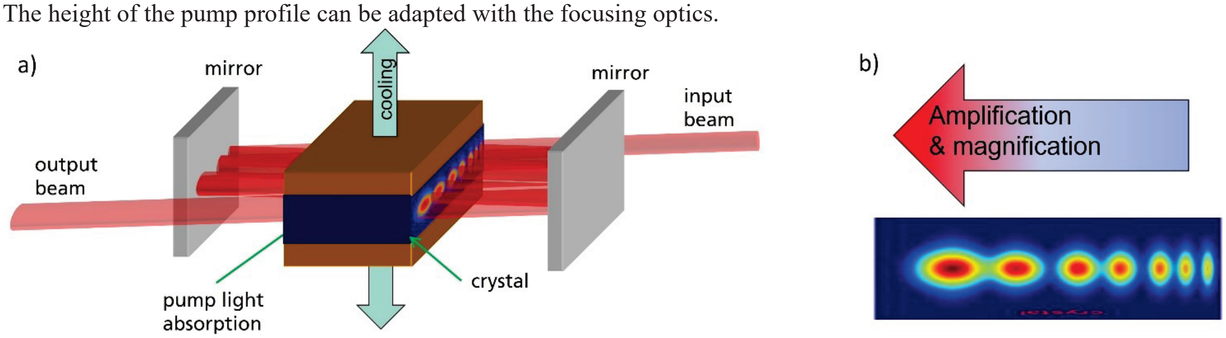

Figure 3. a) Resonator setup of an INNOSLAB amplifier. b) Laser spots for each round trip on the crystal facet. The magnification is adapted to the amplification, maintaining the same fluence at each round trip.

The slab crystal is soldered into a heat sink allowing for 1-dimensional heat removal over the large surfaces leading to a temperature gradient in fast direction but almost no gradient in slow direction, establishing a homogenous thermal lens in fast direction. With these properties the crystal is part of a hybrid resonator (Figure 3) which is stable in the small dimension of the gain volume, where the thermal lens is acting, and is unstable in the large dimension. Usually but not necessarily a confocal arrangement is used, which yields a beam expansion in slow direction by a constant factor depending on the magnification at each round trip through the resonator. The magnification and input beam parameters are matched to achieve equal fluence on the crystal surface and equal gain at each round trip. Hence a constant saturation is kept on the entire beam path through the amplifier. Although multiple passes through the crystal are accomplished, it is still a single-pass amplifier, because a new section of the pumped volume is saturated at each pass, thereby collecting the smallest possible aberration per gain. The hybrid resonator and the aspired mode matching to the gain profile require careful beam shaping with cylindrical telescopes.

In conclusion the main advantages of the INNOSLAB as an amplifier concept for AEOLUS-2 are:

- Simple single-pass amplification with high intrinsic efficiency by a good overlap of amplified mode and pumped volume
- Uniform margin of fluence inside the amplifier to damage thresholds by mode expansion during amplification
- Good beam quality by good thermal management, avoidance of depolarization by birefringence due to a homogenous cylindrical thermal lens
- Insensitivity to uneven diode degradation and single emitter failure due to diode beam homogenization in the slow direction
- High overall gain due to folded beam path
- Short beam path inside the gain medium
- Very compact setup

In the past two decades many INNOSLAB amplifiers addressing different pulse parameters have been set up and tested at ILT.[3] The heritage shows that the best suited setup for extracting 500 mJ pulse energy comprises two INNOSLAB amplifiers. This setup has been realized in the frame of the NIRLI project (section 3.3).

The frequency tripling or third harmonic generation (THG) of the fundamental wavelength will be implemented using a two-stage scheme comprising an SHG (second harmonic generation) and a subsequent SFG (sum frequency generation). The most practical setup to triple the laser frequency is to use critical phase-matching for both conversion stages. Here, a Type I (ooe) process is used for the SHG and a Type II (oeo) process for the subsequent SFG. In both stages, the very mature nonlinear material LBO is used. Because the beam sizes are large compared to the expected walk-off, the walk-off itself will not cause a large effect on the conversion efficiency and the beam quality of the UV output. In addition, the walk-off can be compensated by an inverse alignment of the conversion crystals, hence overall the influence of the walk-off can be neglected here. At the same time the design must take into account the lifetime goal of the laser transmitter. In order to work towards the target of a service life of more than five years in orbit, a low fluence on the surfaces is to be realized in addition to the use of outgassing-free and contamination-free components. In this way, life-limiting effects such as LIC and the formation of color centers are to be avoided as far as possible. Here, a peak fluence of 1 J/cm² UV radiation at the exit surface of the SFG crystal is agreed to be binding, since this value was used in the ALADIN instrument and was approved for good in the AEOLUS mission. To achieve high efficiencies at low intensities, the nonlinear crystals must be large in aperture and length.

2.2 Optomechanics

To meet the requirements and the lessons learned we design and assemble a laser head (LAS) comprising a laser optomechanical assembly (LASO) with the optical components mounted on a monolithic laser bench (base plate) and a hermetically sealed laser housing (LASH) which allows for operating the laser in space under atmospheric conditions (Figure 4). The optical components with high heat dissipation like pump diodes, amplifier crystals etc. are mounted thermally isolated from the laser bench. The dissipated heat is conducted by copper water heat pipes (CWHP) to a thermal interface apart from the base plate, hence the laser bench is rather homogeneously thermalized without disturbing temperature gradients within the base plate. According to our thermal simulations we expect the temperature interval of the base plate to be < 2 K within a typical mechanical interface operational temperature range. The LASO including the heat removal system from the optical components to the thermal interface is designed under the responsibility of ILT.

The thermal interface is thermally coupled to a cold plate by CWHP as well, the cold plate itself is integrated into the laser housing. LASH including the heat removal system from the thermal interface to the cold plate is designed under the responsibility of Airbus DS Germany.[4] The final transport of thermal load from the cold plate to the radiator will be done by loop heat pipes (LHP) under the responsibility of the payload prime contractor.

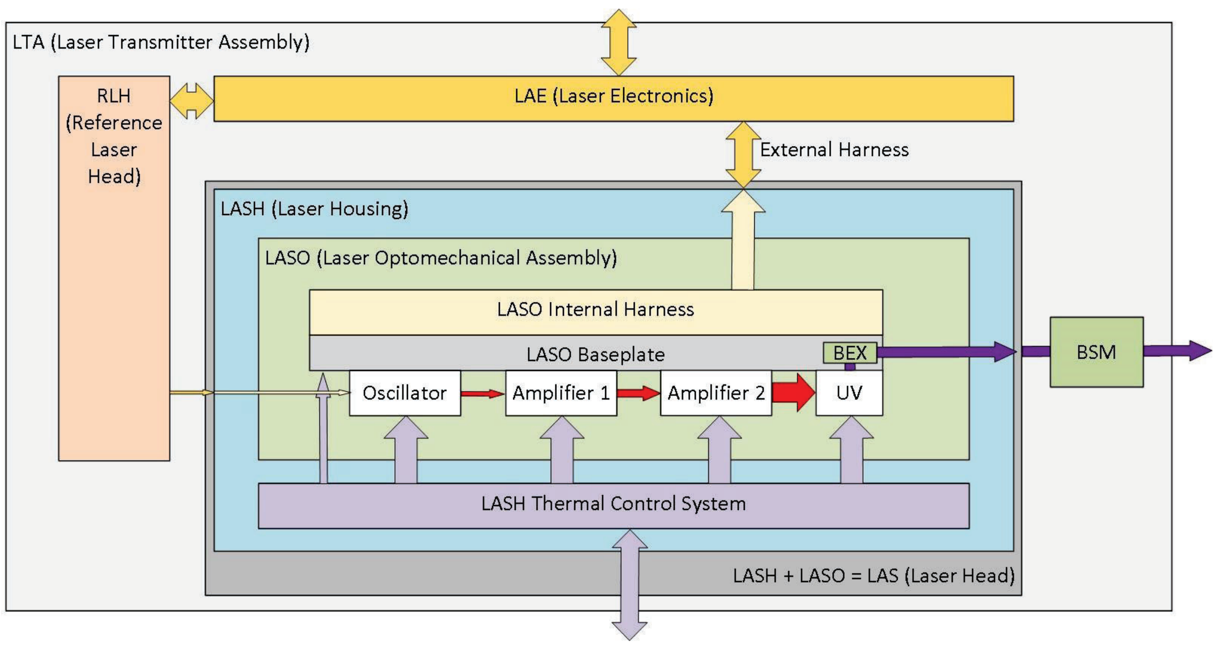

Figure 4. LAS schematics

One key factor for long term stability of the UV laser beam source is cleanliness and the avoidance of organic materials to avoid outgassing and LIC. That means that it is mandatory to mount the optics without any adhesives. Hence all optical components are soldered flux-free to their submounts. In the past we have developed mounting and alignment techniques with extraordinary long term stability characteristics which offer real set-and-forget properties (see chapter 3).

Organic isolation of cables within the electrical harness is forbidden as well. In consequence the electrical harness is built as a pure inorganic design by using a combination of ceramic printed circuit boards and bare metallic conductors.

Overall, the only residual organic parts within the laser housing are little non-avoidable pieces of adhesives used for mounting the micro lenses to the diode laser bars, within fiber connectors and within the piezo actuator.

The entire optomechanical and thermal setup is designed for not only lifetime hands-off operation but also for no need to adjust or align any component by variation of operational setpoints. Only the usual degradation of the pump diodes requires later adjustment of pump currents.

3. HERITAGE

3.1 Overview

The laser concept described in chapter 2 has been developed and verified in several projects for developing or improving airborne and spaceborne lasers in the last 15 years (Figure 5). In these projects most of the optical and optomechanical challenges for the AEOLUS-2 laser have already been mastered.

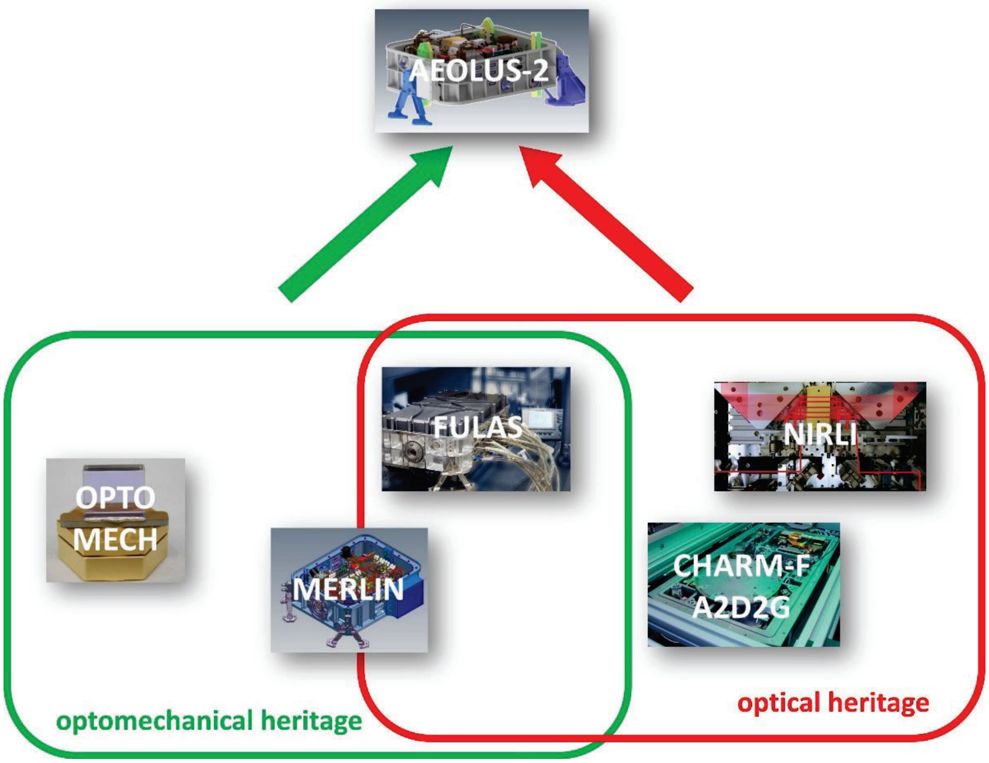

Figure 5. Heritage projects

The optical concept for the AEOLUS-2 laser has been mainly taken from CHARM-F, A2D2G, FULAS and NIRLI while the optomechanics have been developed within OPTOMECH, MERLIN and FULAS as well.

3.2 CHARM-F, A2D2G

CHARM-F is an airborne laser LIDAR system comprising two Nd:YAG MOPA. Both lasers are used for OPO/OPA-pumping in order to generate laser radiation at 1,645 nm for CH_4 detection and 1,572 nm for CO_2 detection. By the use of the previously described oscillator and a one-stage INNOSLAB amplifier about 85 mJ pulse energy are generated for the CH_4 system. For the CO_2 system the energy was boosted in a second INNOSLAB stage to about 150 mJ. The oscillators in both cases deliver single frequency pulses of > 8 mJ pulse energy The pulse duration of both lasers is about 30 ns at a repetition rate of 100 Hz.

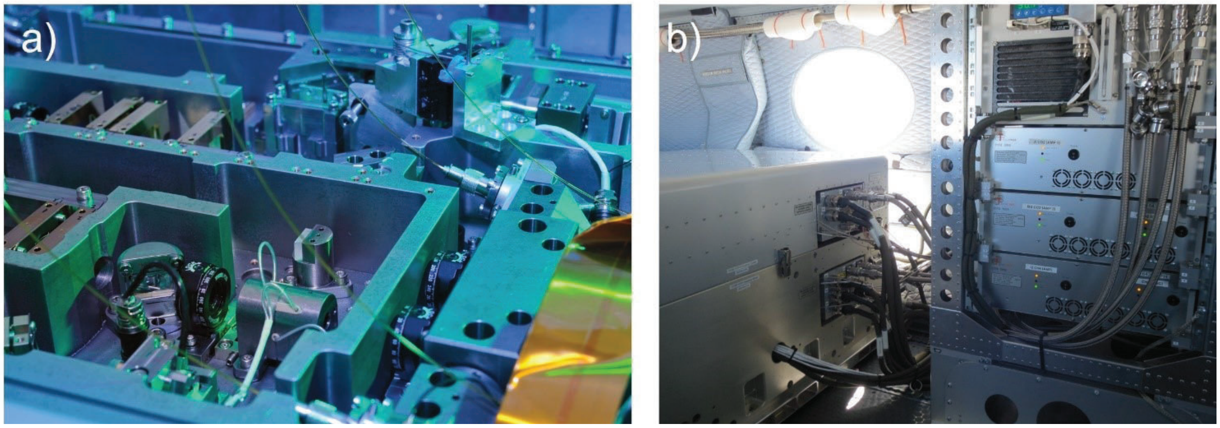

Figure 6. a) assembled A2D2G laser (setup almost identical to CHARM-F CO2 laser). b) CHARM-F laser system mounted in HALO airplane during measurement campaign.

The CHARM-F laser has been mounted into the HALO airplane of the DLR Institut für die Physik der Atmosphäre (DLR-IPA), thus far two successful airborne measurement campaigns have been conducted with the laser system. The lasers showed a reliable and fully hands-off performance during the flights.[5]

A2D2G is an airborne UV laser beam source designed and built to serve as a transmitter for a doppler wind lidar. The optical and mechanical setup is almost identical to the CHARM-F CO_2 laser except for the frequency conversion stage. The fundamental output of the two stage INNOSLAB amplifier MOPA (~150 mJ) has been converted into the UV with a conversion efficiency close to 40 % to a pulse energy > 60 mJ.

The schematics of the MOPA setup of the aforementioned laser systems is depicted in Figure 7, where EP is the pump energy of the different stages. Optical isolators protect the reference seed laser and separate the oscillator from the amplifier stages.

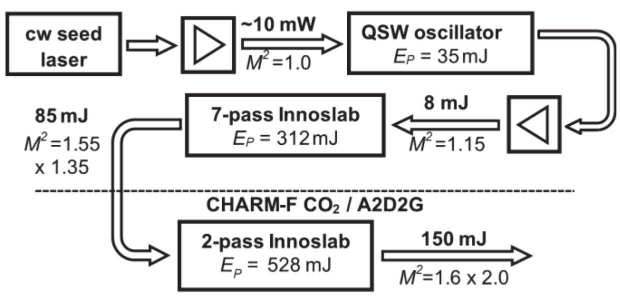

Figure 7. optical architecture of Nd:YAG-based single-frequency INNOSLAB MOPA at 100 Hz repetition rate with representative values for pulse and pump energy. Up to the end of the 1st amplifier stage all setups (CHARM-F-CH4, CHARM-F-CO2, A2D2G) have very similar properties.[6,7]

3.3 NIRLI

The NIRLI laser is a breadboard demonstrator that has been developed to understand and demonstrate the further scaling of pulse energy based on the INNOSLAB design.[8] The NIRLI requirements have been an outcome of the DLR funded AEOLUS Follow On study led by Airbus Defense and Space Germany. This study was a cooperation of the Airbus Defense and Space Germany / ILT laser team together with the Airbus Defense and Space France AEOLUS instrument team with consultancy of members of the AEOLUS science advisory group. The laser comprises the oscillator and INNOSLAB amplifier as described above providing about 85 mJ pulse energy with one subsequent scaled INNOSLAB power amplifier. This MOPA setup (depicted in Figure 8) generates single frequency pulses of up to 525 mJ at 100 Hz PRF and a pulse duration of ~30 ns with an overall optical to optical efficiency of 23 %. The beam quality factor is $M^2_x = 1.8$ / $M^2_y = 1.4$.

To extract > 400 mJ pulse energy from just one power amplifier stage the proven 1st amplifier (energy extraction > 80 mJ) has been scaled by about a factor of 5 while having kept equal the fluence and the gain in transversal direction from the beam to not increase the danger of LID and parasitic lasing.

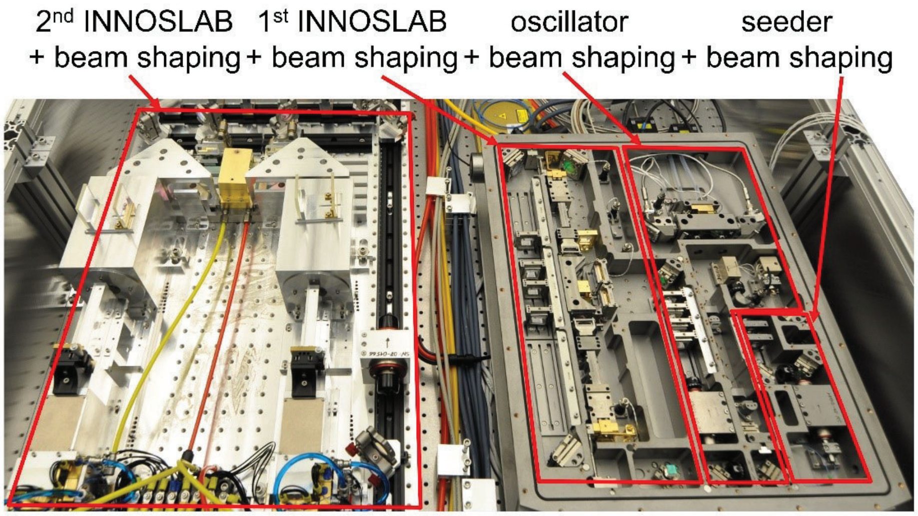

Figure 8. NIRLI breadboard demonstrator. On the right the oscillator and pre-amplifier in the flight proven design, on the left the power amplifier with Faraday isolator between the INNOSLAB stages.

This laser has been equipped with a subsequent OPO/OPA stage to convert the wavelength to 1,645 nm, which is the wavelength for CH_4 detection addressed by CHARM-F and MERLIN. In this configuration the NIRLI laser has been operated for performing LIDT testing for MERLIN at 1,064 nm and at 1,645 nm on a daily basis for over a year.

The schematic of the NIRLI setup is depicted in Figure 9. To avoid parasitic lasing by coupling of the two amplifier stages they are separated by Faraday isolators. Given the achieved pulse length, the pulse energy and the excellent beam quality, the NIRLI laser is a breadboard demonstrator for the infrared section of AEOLUS-2 which meets the crucial requirements at twice the PRF required for AEOLUS-2.

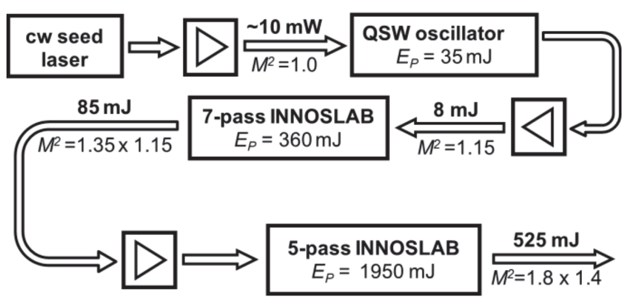

Figure 9. Optical architecture of NIRLI (100 Hz PRF).[8]

3.4 OPTOMECH

The stability requirements of the optical output beam require a thermally and mechanically stable mounting of the optical components. Goal of the OPTOMECH projects was to find or develop mounting techniques for the oscillator and INNOSLAB amplifier components which are suited for spaceborne applications with only inorganic material. Key components are mirror mounts and lens mounts, but also Pockels cells and Faraday isolators. Typically, the mirrors are the most alignment sensitive elements in a solid state laser system because they add the highest contribution to misalignment and pointing. The required stability strongly depends on the laser requirements and the laser design, but experimental and numerical tilt analysis of the described lasers show that long term stabilities of less than 10 µrad have to be fulfilled, and typical operational and non-operational temperature intervals for spaceborne applications are +10 °C .. +30 °C and -30 °C .. +50 °C respectively. A thorough screening of the market and the examination of several commercial mounts showed that none of the available mounts fulfilled the needs concerning stability and mass. Hence it was necessary to develop new mounts.

In consequence mirror mounts have been developed with only screw and solder joints and no organic subcomponents.[9,10] The soldering technique was inherited from the development of soldered diode bars and soldered laser crystals. The optics' mechanical interface to the laser baseplate is given by a submount made of metal, typically aluminum. This submount is connected to the baseplate with a screw interface, which is just for fixation but not for alignment tasks. An electrically isolating ceramic plate is soldered on the top side of the submount, which is equipped with a metallic coating on the surface on which the optics is soldered (Figure 10a).

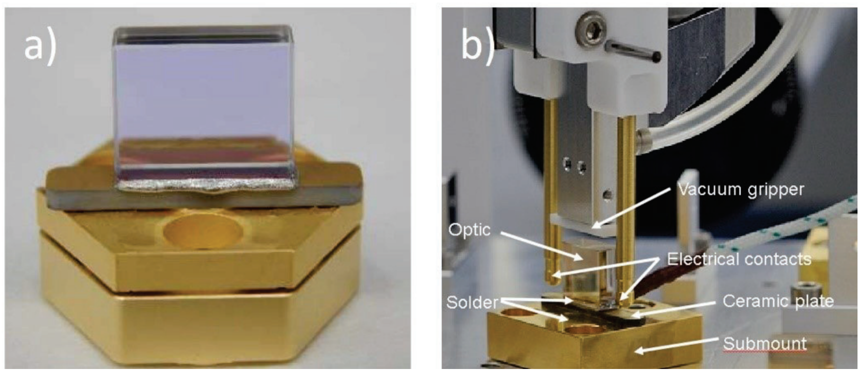

Figure 10. a) OPTOMECH mirror mount. b) Alignment procedure.

For alignment after screwing the mount on the laser bench the optics is gripped with a vacuum gripper which is connected to a micromanipulator capable for precise adjustments in the sub-µrad range. Two electrodes get contacted to the metal coated ceramics and by electrical current the metal coating and the solder interface are heated up to the solder's liquid phase. After alignment with the micromanipulator the heating current is stopped and the solder solidifies.

For qualification the mounts undergo environmental tests (thermal and vibrational) to verify their compliance to the tilt stability requirements, especially each mount for space application is tested before integration. For thermal testing the mounts are screwed to test plates which serve as reference for angular measurements. This setup is placed in a climate chamber and a temperature test profile covering non-operational and operational temperature ranges is applied. The angular displacement of the mirror with respect to the test plate is measured online. A typical test result is depicted in Figure 11. It shows that the angular displacement within the operating temperature range is way below 10 µrad and thus well within specification.

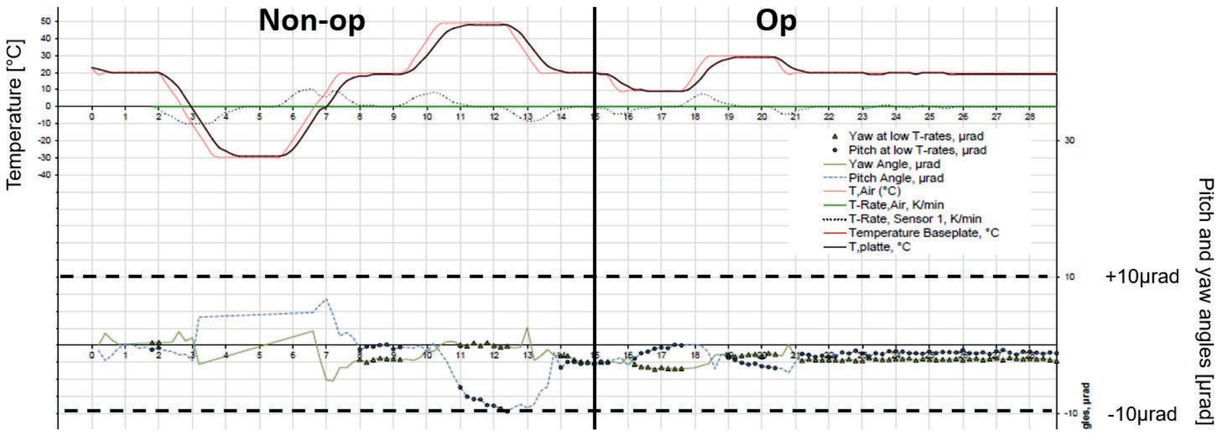

Figure 11. Typical environmental test results of an OPTOMECH mirror mount. Top: Non-operational and operational temperature profile. Bottom: Tilt angles of the mirror with respect to the baseplate.

For vibrational testing the non-operational random vibration spectrum as described in Table 2 is applied to the mount screwed to a reference test plate for two minutes by a low force shaker. The tilt of the mounts is measured before and after the vibration tests for all axes (x, y, z). In case of proper mounting all mounts show a tilt deviation of less than 10 µrad after vibration testing.

Table 2. Non-operational random vibration spectra for OPTOMECH mounts

Frequency /Hz	20	50	800	2000
ASD /(g^2/Hz)	0.026	0.16	0.16	0.026

A solderable organic free package has also been developed for Faraday isolators, Pockels cells and nonlinear crystals.[10] Because those are transmitting optics their alignment stability is less critical compared to mirrors except for nonlinear crystals whose conversion efficiency depends on the angle and the temperature. BBO Pockels cells and TGG Faraday isolators are depicted in Figure 12. For qualification these components undergo environmental tests as well. Their optical performance has been measured in test setups and in breadboard solid state lasers. It showed no difference to conventionally set up Pockels cells and Faraday isolators. The electrical stability of the Pockels cell package has been lifetime tested in a special designed setup in which up to 6.2 billion high voltage switching pulses are applied to the BBO crystal under varying environmental conditions. No unusual behavior or sparking was observed.

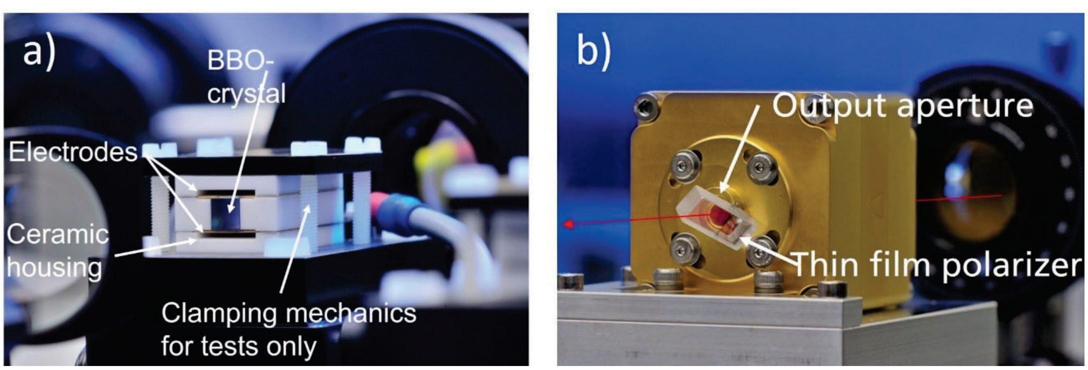

Figure 12. a) Laboratory demonstrator of the soldered BBO Pockels cell package. b) Faraday isolator with soldered thin film polarizer and TGG crystal.

3.5 FULAS

Goal of the FULAS project was to design and build an engineering model for a spaceborne LIDAR laser transmitter, proving the optical concept of CHARM-F and the optomechanical concept of OPTOMECH to be suited for space applications in terms of pulse parameters, repetition rate, robustness, spectral properties, thermal and mechanical stability.[11,12] The optical architecture as depicted in Figure 13 is a MOPA comprising a single frequency seeded and actively controlled electrooptically q-switched Nd:YAG rod oscillator and a Nd:YAG INNOSLAB amplifier, the optical design is identical to those realized in CHARM-F, A2D2G and NIRLI with the only difference to CHARM-F and A2D2G being their slightly longer oscillator resonator length for adaptation of pulse duration.

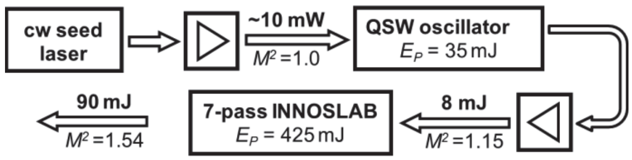

Figure 13. Optical architecture of FULAS at 100 Hz PRF. The comparably low efficiency is due to a non-optimized fast axis divergence angle of amplifier pump diodes.

The optical components are mounted on both sides of an optical bench which is isostatically mounted inside the housing frame and therefore is isolated from stress induced by the instrument environment. To reduce LIC effects, the hermetically sealed housing of about 500x200x300 mm³ provides lifetime atmospheric pressure conditions for the laser optical system. The central frame of the housing provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for miniature LHP and a beam exit window. An external cold plate attached to the central frame of the housing serves as condenser for the LHPs and as overall system thermal interface (Figure 14).

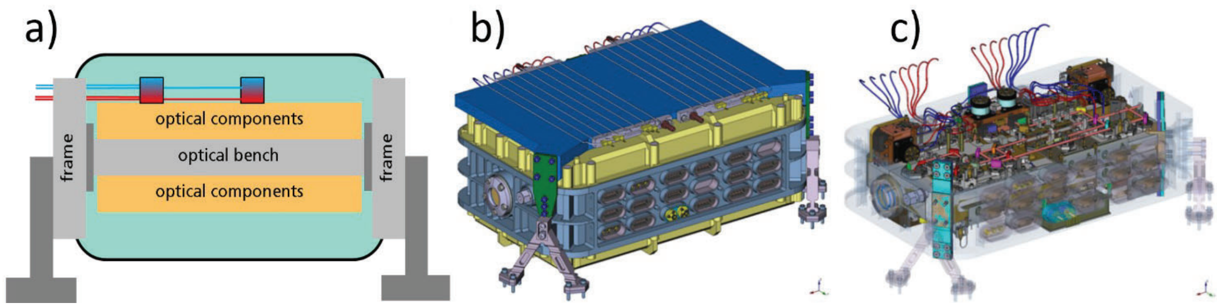

Figure 14. a) Structural scheme of FULAS. b) Pressurized housing with top-mounted cold plate. c) Internal optical bench.

Organic-free joining techniques are used to realize an all metallic, ceramic or glass design with just a few exceptions (for instance for fiber connectors). The final sealing of the covers to the frame is done by welding. To allow for an efficient removal of about 100 W thermal load inside the pressurized housing and minimize thermal gradients across the optical bench, miniature LHP are directly attached to the major heat sources inside the laser housing, hence almost no heat is coupled into the base plate. The electrical harness is made of ceramics and metal straps only.

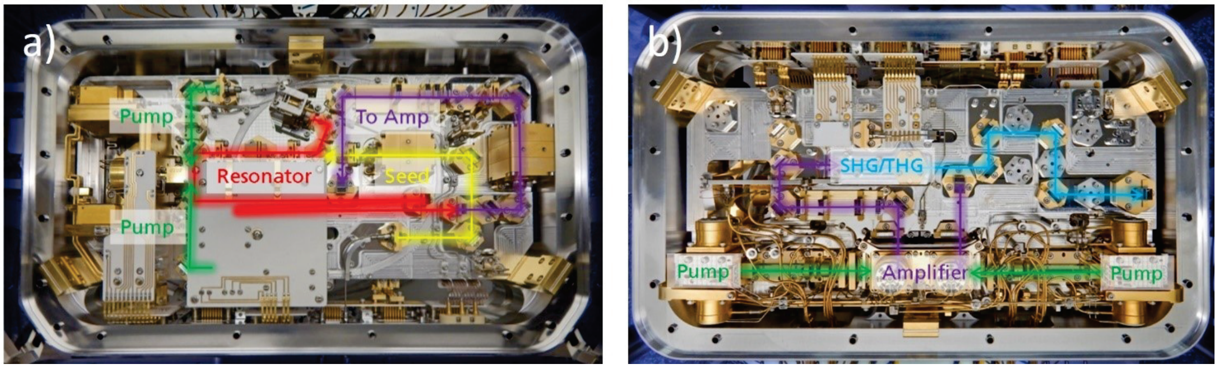

Figure 15. a) Optical bench with beam paths: Seeder, oscillator pump and resonator on bottom side, b) Slab pump, amplifier and UV conversion by SHG/THG (2nd/3rd harmonic generation, not implemented yet) on top side

The extraordinary stability of the thermomechanical and optomechanical concept became already obvious during assembly and integration (AIT). During the entire AIT process it was never necessary to realign any optical component once it was set. The oscillator was integrated on one side of the laser bench whilst the other side of the bench (the amplifier side, see Figure 15) remained empty at first. The oscillator performance stayed absolutely stable during the entire following AIT process, even after turning the laser bench and integration of the amplifier with its higher thermal dissipation.

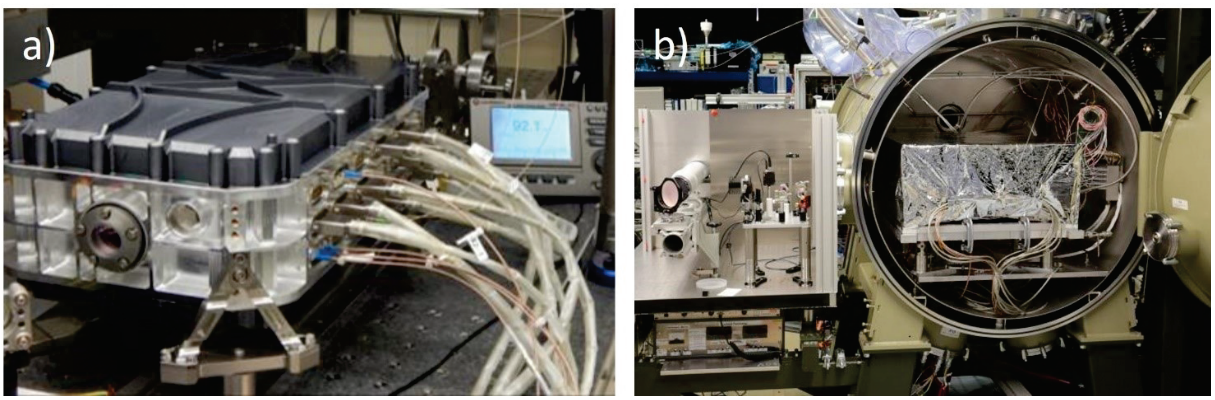

Figure 16. a) Final integrated laser head during first performance test. b) Thermal vacuum test facility with integrated laser and external test setup for online laser performance measurement.

The temperature and pressure related performance parameters of the FULAS technology demonstrator have been verified with thermal vacuum tests. The vacuum chamber has been evacuated and within one week the thermal interface temperature has been varied in a 4 K range, and the mechanical interface temperature in a 10 K range. The laser performance has been verified by constantly measuring and recording the major performance parameters (pulse energy, beam profile, pulse width and beam pointing). For the non-operational test the laser has been kept 34 days under vacuum. During this time five temperature cycles (two in the range -10..50 °C and three in the range -34..50 °C) were carried out. After each cycle the laser performance was verified. In each performance test before, during and after the thermal vacuum tests no significant performance changes were measured, proving the excellent thermal stability of the optomechanical design.

3.6 MERLIN

Within the ongoing MERLIN project Airbus and ILT have designed a laser beam source for the Methane Remote Sensing LIDAR Mission (MERLIN) conducted by the French Space Agency CNES and the German Space Administration DLR.[13]

The laser transmitter is to generate double pulses with > 9 mJ pulse energy and 20 Hz PRF at ~1,645 nm wavelength with > 10 ns pulse duration. The optical architecture is depicted in Figure 17.

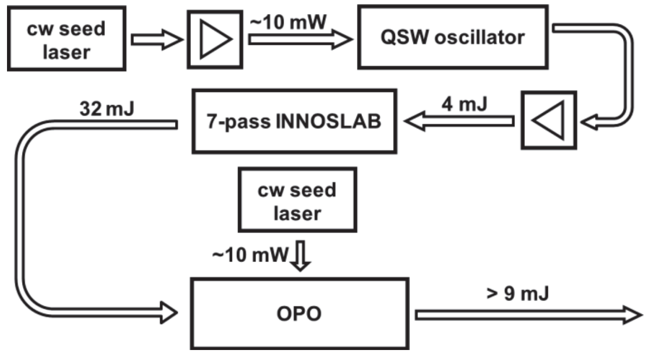

Figure 17. Optical architecture of the MERLIN laser with 20 Hz double pulses with a time interval of 300 µs between the pulses.

To generate 9 mJ single frequency pulses on the methane wavelength an OPO with controlled cavity length has to be pumped with ~32 mJ pulse energy at 1,064 nm wavelength. The compared to the aforementioned lasers little pulse energy and shorter pulse duration require a different oscillator design, and a slight adoption of the INNOSLAB amplifier design. However, the general requirements to the thermal and optomechanical stabilities do not change. The optical design has been verified by a laboratory breadboard demonstrator.

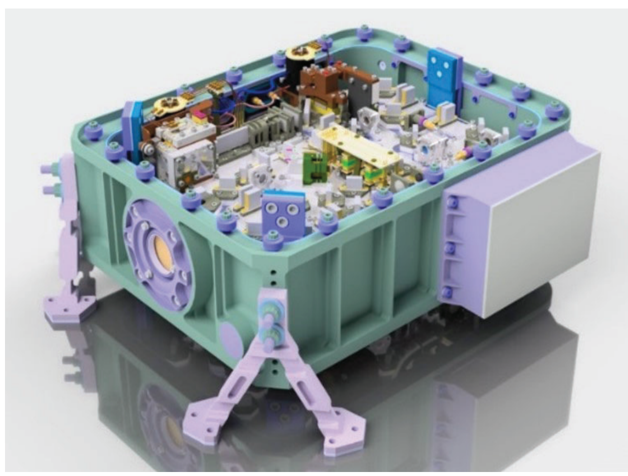

Figure 18. CAD Model of the MERLIN laser with open housing.

The optomechanical design builds on the results and the lessons learned from OPTOMECH and FULAS. The laser is assembled on both sides of a stable laser bench which is isostatically mounted into a hermetically sealed laser housing allowing to operate the laser under normal atmospheric conditions in space. The optomechanical components developed in OPTOMECH have been fully space qualified by testing the components and sub-assemblies with all thermal and mechanical qualification loads including shock. This includes the nonlinear crystals for the OPO, whose soldering is challenging due to their birefringence.

The electrical harness, usually a major contributor for outgassing organic material, is developed and built in a completely inorganic design avoiding any plastics insulation by using a combination of ceramic printed circuit boards and bare metallic conductors. All components are either CTE-matched or CTE-compensated and space qualified by environmental and shock tests as well.

To avoid LHP feedthroughs for each heat dissipating component the thermal design is different from the one in FULAS: in MERLIN the heat is conducted away from the main heat sources by massive metal stripes to two thermal interfaces.

The final transport of the thermal load from this interface is done by two miniature LHP directly routed through the laser housing towards the radiator, hence reducing the number of feedthroughs.

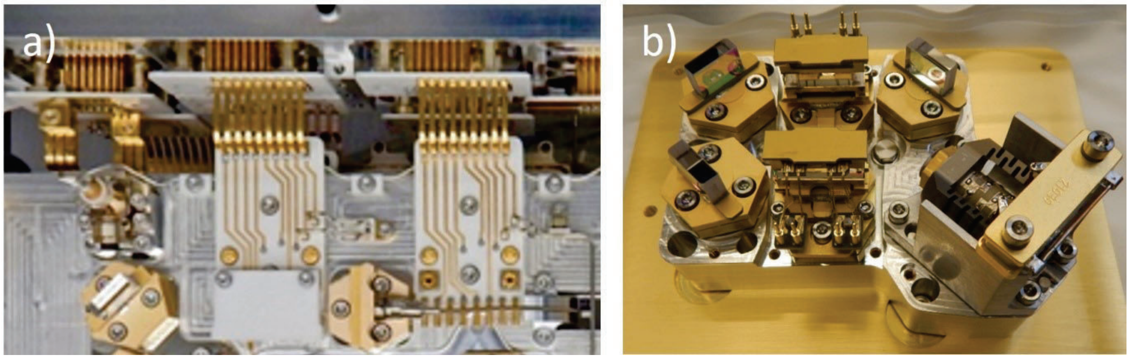

Figure 19. a) Organic free electrical harness. b) Fully space qualified OPO including piezo actuator and solder packaged nonlinear crystals.

At present the MERLIN engineering qualification model (EQM) and the flight model (FM) are assembled and integrated.

3.7 Conclusion

Consequently, we have shown in the sections above that many of the requirements and lessons learned issues listed in chapter 1 have already been fulfilled or considered in our previous projects:

- The optical architecture for the infrared part of the laser has been proven. The oscillator design of the AEOLUS-2 laser is identical to NIRLI and FULAS except that the thermal lens of the AEOLUS-2 laser is a little weaker due to the lower PRF which increases the spot sizes on the optical surfaces and hence relaxes the fluence in the oscillator. The oscillator resonators of CHARM-F and A2D2G are just a little longer. The design of the 1st INNOSLAB amplifier is identical to the ones in CHARM-F, A2D2G, FULAS and NIRLI.
- The required pulse parameters in the infrared (pulse energy, pulse duration, beam quality, spectral properties) have been demonstrated within the NIRLI project, making the NIRLI laser a laboratory breadboard demonstrator for the infrared section of AEOLUS-2
- All components needed for oscillator and 1st amplifier have been fully space qualified
- The optomechanical and thermal concept realized in FULAS and MERLIN takes into account the lessons learned from AEOLUS in terms of isostatic mounting, pressurized housing, avoidance of organic materials and keeping heat sources away from laser bench and alignment sensitive components.

4. DEVELOPMENT ISSUES FOR AEOLUS-2

Building from the heritage projects the remaining development issues while designing and building the AEOLUS-2 LTA EM are:

- Transferring the optical concept proven in NIRLI to the FULAS/MERLIN platform, scaling the MERLIN proven optical components for the 1st INNOSLAB amplifier to set up the power amplifier and the frequency conversion unit.
- Demonstrating the frequency conversion to generate UV pulses with > 150 mJ pulse energy at fluence levels below 1 J/cm^2.
- Adapting the electrical harness.
- Adapting the heat removal system to the higher heat dissipation compared to FULAS and MERLIN.

A scaled laser bench has been designed as well as the optomechanical components for the power amplifier and the frequency conversion unit. The entire LASO including the organic free electrical harness has been accommodated using CAD software (Figure 20).

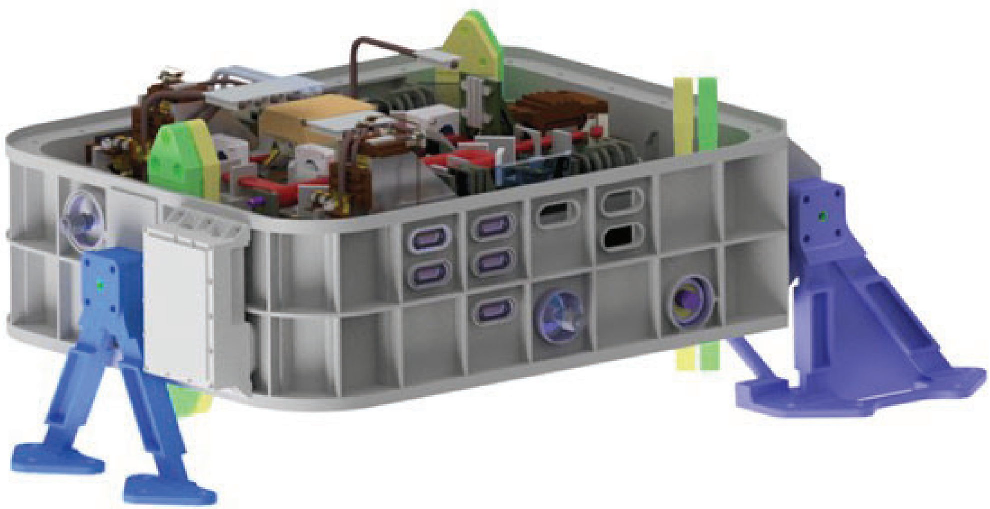

Figure 20. Complete CAD model of the AEOLUS-2 LTA EM

The frequency conversion has been modeled, the models have been verified with the results from the frequency tripling in A2D2G and other experimental setups. At present the frequency conversion concept is tested and verified using the NIRLI laser as the pump source.

For heat removal an optimized thermal architecture based on the lessons learned from FULAS and MERLIN has been designed. This new thermal management concept is required because of the higher power consumption and increased number of heat sources inside laser. In FULAS each heat source is directly connected to dedicated LHPs, with which the heat is transferred through the housing to the outside mounted cold plate. In contrast the heat emitting components of the MERLIN laser are connected by metallic structures to two thermal interfaces. From these interfaces, the heat is conducted out of the housing by two miniature LHPs, hence reducing the number of feedthroughs and the complexity of the heat removal system.

Due to the higher amount of heat dissipating components in the current laser the FULAS approach is not feasible. In total, there are nine different components that need to be connected to the thermal harness. Some of them, e.g. the pumps of the second amplifier, have several interfaces for dissipating the heat load equally. For each interface a separate LHP would be required, which would increase the system complexity and mass.

Metallic connections like in the MERLIN concept are not applicable because of the highly increased dissipated heat. Large cross sections of the metal beams would be necessary to conduct the heat with an acceptable temperature gradient. But even then, the operating temperatures for some components are difficult to achieve. Finally, the MERLIN concept would cause additional mass of several kilograms because of the massive copper structures and higher component temperatures due the high amount of heat.

For the AEOLUS-2 LTA EM each heat source is connected to one of two main thermal interfaces inside the laser housing via a system of CWHP (Figure 21). The CWHP is a passive system transferring the heat by the phase shift of the internal water from the hot evaporator end to the cold condenser end. In this way the thermal resistance is reduced by one order of magnitude compared to metallic connections. In total this technology leads to a highly efficient, compact, and much lighter internal thermal harness and allows to reach the optimum working point for each component more easily.

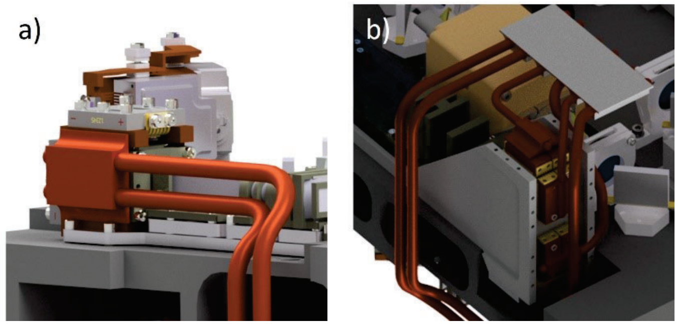

Figure 21. a) Preliminary routing of copper water heat pipes at 1st amplifier pump diodes b) and at 2nd amplifier pump diodes

5. CONCLUSION AND OUTLOOK

We have described the optical and optomechanical concept for a laser transmitter for the AEOLUS-2 mission. Most of the requirements and lessons learned have been addressed in previous projects, including the demonstration of the infrared pump laser and space qualified components. The design is subject to the detailed review by ESA at the end of this year.

6. ACKNOWLEDGEMENTS

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