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MERLIN High Energy Laser Source for Methane Sensing at 1645 nm

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ABSTRACT

MERLIN (Methane remote sensing LIDAR mission) is a joint DLR/CNES mission, which will measure column densities of methane in the Earth atmosphere. The heart of the instrument is the laser transmitter subsystem, developed and built by Airbus (Ottobrunn, Germany) in cooperation with the Fraunhofer Institute for Laser Technology (Aachen, Germany), being in charge of the laser's optomechanical assembly. The project is currently in Phase D with an expected instrument delivery date to the satellite prime in 2026 and launch in 2028.

The laser system features key technologies, as already demonstrated successfully in the frame of the FULAS project, to enable reliable long term and high-stability laser performance operation under space conditions. The technologies are optimized with respect to thermal and mechanical stability and developed with special attention on LIC (laser induced contamination) issues by aiming for a fully inorganic design, avoiding any critical organic and outgassing materials.

This publication provides an insight into the system design. Furthermore first results from the ongoing qualification model assembly and integration activities are presented, including evidence of the technology maturity for space, based on subassembly and component level qualifications as well as representative bread board activities.

Keywords: LASER, LIDAR, DIAL, IPDA, MOPA, MERLIN, methane,

1. INTRODUCTION

The MERLIN Payload is an IPDA (Integrated Path Absorption) LIDAR which emits two narrowband pulses per pulse repetition interval at two slightly offset wavelengths of approximately 1645 nm. The "On-line" pulse (referred as λ_{on}) at 1645.552 nm targets a strong absorption peak of methane, while the "Off-line" pulse (referred as λ_{off}) around 1645.825 nm provides a reference for the absorption and scattering of the atmospheric column outside the absorption feature [1][2]. The absolute methane concentration is then calculated based on the differential atmospheric absorption between the two wavelengths, taken from relative intensity measurement of the signal reflected on earth surface. The technical complexities of this system are shared between the laser as emission unit at the one end, due to the high systematic stability and performance requirements, and the Avalanche Photodiode (APD) based detection chain at the other end, due to the high sensitivity requirements to guarantee sufficient SNR and radiometric stability.

While a more general overview of the MERLIN instrument is given in [3], which is published in the same issue of these proceedings, this paper focuses on one of the Payload's core subsystems, namely the laser assembly [4]. The laser assembly is divided into three functional sections: The master oscillator, the optical amplifier (Master Oscillator Power Amplifier Scheme) and the Optical Parametric Oscillator (OPO). The seeded oscillator cavity features a Pockels cell for Q-switching and a Piezo element for controlling the frequency stabilized single-longitudinal-mode operation through precise cavity length control (dithering technique). The architecture of the oscillator is based on a double-side end-pumped rod in 'twisted mode operation' to avoid spatial hole burning in the Nd:YAG crystal. The amplifier follows the Innoslab design offering superior thermal management characteristics, low risk for parasitic oscillations and very stable thermal lensing. The OPO section follows a novel design comprised of two thermally controlled KTP crystals in an actively stabilized ring resonator. Pumped by the 1064 nm pulses provided by the MOPA, this specific design is optimized for uniform amplification of both seeded operational wavelengths of a pulse pair, separated by a fraction of a nm, with adequate stability in the energy, frequency and spatial domain.

To meet the high thermomechanical stability requirements there had been some further design challenges. The active laser elements are cooled with a regulated Loop Heat Pipe (LHP) thermal control system to minimize heat loads towards the baseplate [2]. Further, to minimize heat generation, the laser operates at a high optical - optical efficiency scheme [4]. At component level, the Fraunhofer Institute has developed a novel “Optomech” technology. While this technology provides outstanding tilting stability of the optics over large temperature ranges, it also almost completely eliminates the need of organic and glue materials inside the laser, which are well known to provoke catastrophic failures in laser systems. As this is of crucial importance in specific for UV laser systems to ensure a sufficient lifetime of the laser inside a sealed housing without need for on-board gas supply, this approach is also seen as enabling technology for future missions like e.g. AEOLUS 2 [8].

Here we present recent test results of laser components and subassemblies built for the MERLIN laser engineering and qualification model (EQM), which not only demonstrate the high performance capabilities of the mentioned technologies, but also prove the flightworthiness and maturity of the technology (TRL).

2. SYSTEM OVERVIEW

2.1 Laser transmitter subsystem architecture

Table 1: Major Laser performance parameters (left) and environmental requirements (right)

Parameter	Value
Wavelength range	1645.5 -1645.9 nm
Transmitted Pulse Energy	> 9 mJ
Pulse Repetition Frequency	2x20 Hz
Centre Wavelength Accuracy	10 MHz wrt. Seed
Pulse Duration	> 10 ns
Spectral Purity	99.95 %
Pointing Stability (short term)	100 µrad

Parameter	Value (Qual. Level)
Mechanical loads: - Quasi static - shock	 28 g 400 g
Thermal loads: - Non-Operation - Operational	 -25 °C … +50 °C 0 °C … +30 °C

The mission critical laser performances as given in Table 1 are directly derived from the instrument requirements [7]. For fulfillment, the operational functions of the MERLIN Transmitter Subassembly (TxA) [2] are distributed over several subsystems as illustrated in Figure 1 and explained hereafter:

- The Laser head (LAS) with dimensions of about 350 x 450 x 210 mm², comprised of three modules, with more details on that given in the next section.
    - The opto-mechanical assembly (LASO), which is built by a central optical bench, equipped at both sides with the opto-mechanical components of the laser. To decouple from environmental loads caused by variation of temperature, variation of environmental pressure and mechanical loads from S/C during launch, it’s isostatic mounted towards the central frame of the
    - Hermetic housing (LASH), which is hermetically sealed by welding to provide a stable pressurized environment for the LASO. It comprises all necessary interfaces to operate and monitor the laser by means of electrical, fibre optical and thermal feedthroughs as well as a welded beam exit window.
    - The loop heat pipe based thermal control system is hard mounted to the LASH via thermal feedthrough tubes. While the evaporators of the Loop heat pipes are attached internally of LASH directly to the main heat sources of LASO, its condensers are connected externally to a dedicated radiator.
- The Laser Electronics Unit (LAE) for all electrical supplies and control functions of the laser head, i.e. powering the laser pump diodes, providing thermal control, performing the closed loop cavity control of the laser master oscillator and driving the two Piezo actuators of the laser master oscillators linear cavity and the optical parametric oscillators ring cavity. While the main functions are combined in one box (LAE-U) remote of LAS, the high

voltage switch to operate the LASO oscillators Q-switch is situated in an additional small box (LAE-P), directly mounted onto the LAS housing.

- The Frequency Reference Unit (FRU), for measurement and stabilization of the emitted wavelength. It provides the stabilized optical seed signals for the laser OSC at about 1064 nm, and the two optical seed signals at both operational wavelengths around 1645 nm for the OPO. Based on an internal wavelength measurement of the optical feedback extracted from the emitted LAS laser pulses, the FRU also generates the feedback command towards LAE for closed loop OPO cavity control.
- The separation unit of the internal calibration chain (ICC-S), to extract this optical feedback from the emitted double pulses and provide to FRU for closed loop OPO cavity control.

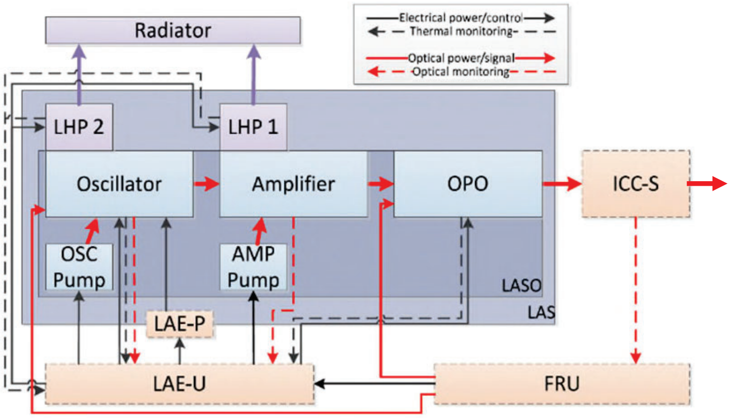

Figure 1: Functional architecture of the MERLIN laser transmitter assembly

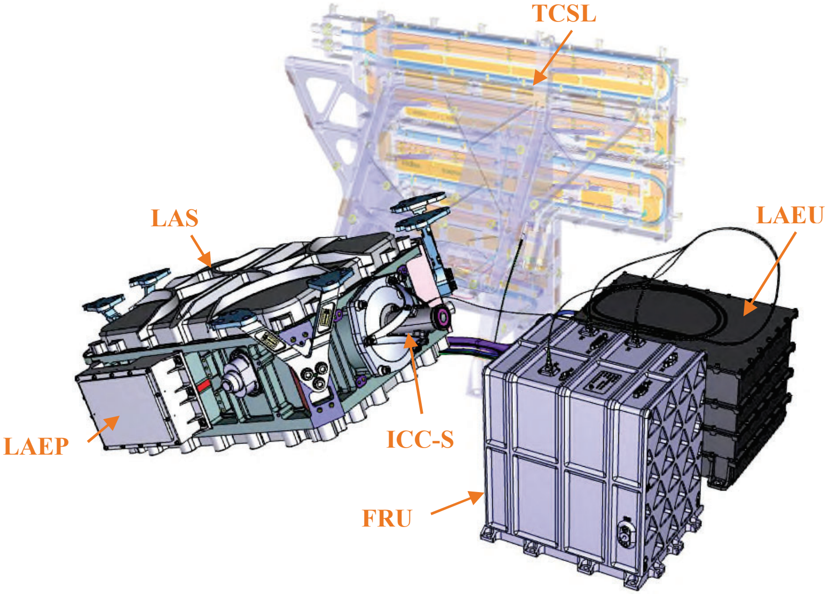

Figure 2: CAD model of the MERLIN laser transmitter assembly

2.2 Laser architecture

The MERLIN Laser architecture is relying on the heritage architecture already proven in the frame of ESA's FULAS technology project [6]. It's founded on two major design criterions: at first a strict thermal decoupling of the laser baseplate from environment and second the avoidance of organic materials known to foster laser induced contamination effects.
Therefore the core optical bench is mounted symmetrically with use of three isostatic mounts into the housing (see Figure 3), effectively decoupling the optical assemblies from environmental effects by change of pressure or temperature. The heat generating laser-active components are mounted thermally insulated towards the optical bench and the heat is removed by LHPs linked directly to these sources. This results in a very uniform temperature distribution over the entire baseplate. Combined with the outstanding high thermal-mechanical stability of the optomechanical mounts [5], this enables operation over a wide environmental temperature range at ambient as well as vacuum and still meeting all its performance and stability requirements without any active thermal stabilization of the baseplate or the need for adjustable components to realign any of its sections.

To ensure a maximum lifetime in a sealed pressurized housing, the amount of outgassing organic materials is close to be eliminated by establishing a specific mounting technology relying on optical mounts (so called C-mounts) with solder interfaces only instead of gluing the optics. That technology also allows for an outstanding mount stability of better than 10 µrad tilting within an operational temperature range of 20 K. Also the electrical harness, usually a major contributor for outgassing organic material, is built as a pure inorganic design. Skipping any flexible wiring posed significant challenges on the harness design, since all its components have to be either CTE-matched or CTE-compensated. But at the end, all harness is successfully implemented as combinations of ceramic printed circuit boards and bare metallic conductors.
The laser optical assembly is based on industrial state-of-the-art diode pumped solid state laser technology. It can be divided into three functional blocks as shown in Figure 1. A frequency stabilized Nd:YAG Master Oscillator (OSC) with subsequent Power Amplifier (AMP) to pump an optical parametric oscillator (OPO). The temporal and geometrical properties of the OPO pump beam are generated in the low-power (~4 mJ) frequency-stabilized Nd:YAG oscillator. Its spectral properties are controlled by seeding with the target wavelength around 1064 nm (provided by FRU) and use of a piezo driven mirror for cavity control. The generated ns-pulses are amplified in the subsequent amplifier stage, designed to increases the pulse energy (~30 mJ) without changing other beam properties. This beam is used for pumping the OPO to convert the optical energy into the two final scientific wavelengths around 1645 nm. As for the master oscillator, the temporal and geometrical properties of the emitted pulses are generated in the OPO and its spectral properties are controlled by seeding with the target wavelength and use of a piezo driven mirror to tune the OPO ring cavity. Here the used OPO design and OPO cavity control algorithm enables tuning of the cavity for both required wavelengths at the same time. By alternating seeding of the OPO with either the On-line or the Off-line wavelength provided by an optical fiber link from FRU, both wavelengths required for a differential absorption LIDAR are generated sequentially out of the same optical cavity with about 300 µs temporal separation.

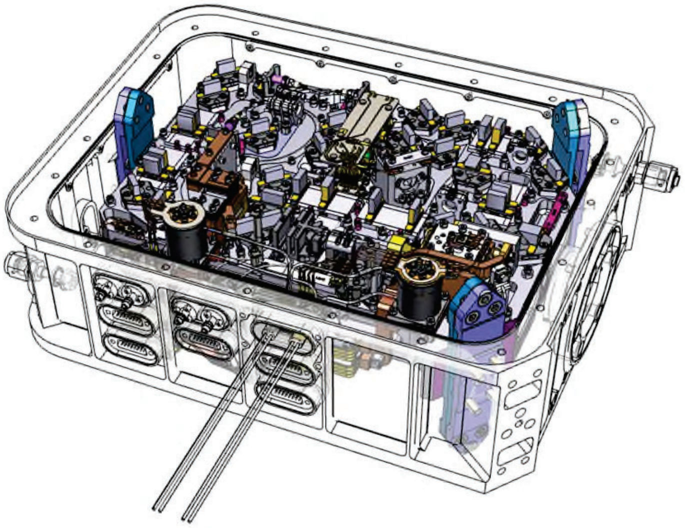

Figure 3: CAD model of the laser optical assembly integrated into the central frame of the laser housing

3. FLIGHTWORTHINESS AND TECHNOLOGY MATURITY

3.1 Pressurized hermetical Housing Verification Assemblies

The fundamental design of the housing was already demonstrated in the frame of the FULAS activities. In parallel to the manufacturing and assembly of the MERLIN LASH qualification model, a qualification program had been performed on representative samples and subassemblies, including all processes (surface treatment and several welding processes) and components (Hermetical Electrical Sub-D and High Voltage, fiber optical, gas filling port and LHP tube feedthroughs as well as optical beam exit window) following the “none-organics” design rule.

For that qualification program, the whole manufacturing, processing and assembly chains of the LASH had been executed with help of representative breadboards. These assemblies have fulfilled environmental test campaigns to raise the technology and design to TRL 7.

3.2 Laser Transmitter Subsystem Breadboard (TxA-BB)

The TxA-BB was the first campaign for successful performance demonstration of the MERLIN Laser optical design, featuring a functionally representative breadboard model of LASO together with the engineering models (EM) of FRU and LAE (Figure 4). The used LASO BB is a laboratory setup [4], representative to the flight design with respect to its optical properties and the electrical and optical interfaces to LAE and FRU. The optics are mounted using conventional mounts, so that more parameters can be monitored and the system is more flexible compared to the soldered flight design. The limitation of that laboratory setup is, that the breadboard is not representative concerning the mechanical and thermal properties and stabilities.

This campaign took place at ILT premises in 2019. The purpose of the campaign at this level was to demonstrate the performance of the mentioned cross-unit functions and the system capability to meet the stringent performance requirements considering the limitations of the early unit models and in particular of the LASO BB model, which was exposed to laboratory conditions and related thermal and mechanical instabilities.

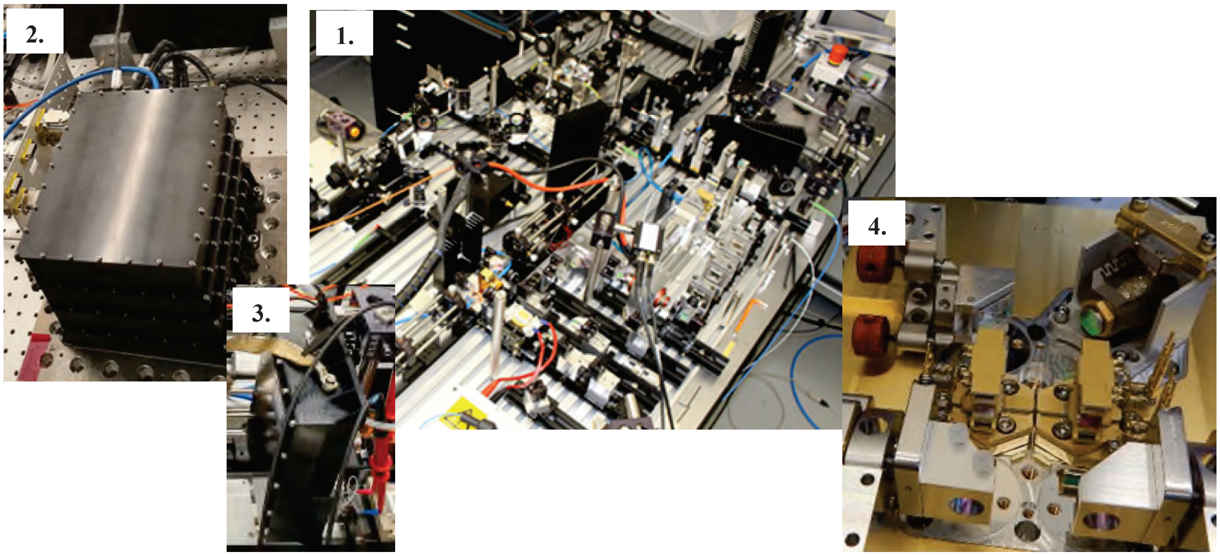

Figure 4: TxA-BB (1), operated by EM of LAE-U (2), LAE-P (3), FRU (not shown) and functional representative OPO (4) with flight like crystal oven mounts.

With the measured performance parameters, including energy and pointing stability, wavelength accuracy and spectral purity, the capability of the system to fulfill the most critical performance requirements as listed in Table 1 is proven (see exemplary measurements in Figure 5). The few outliers are attributed to the mentioned instabilities of the environment. Notably, the system achieved spectral purity benchmarks of better than 99.95%.

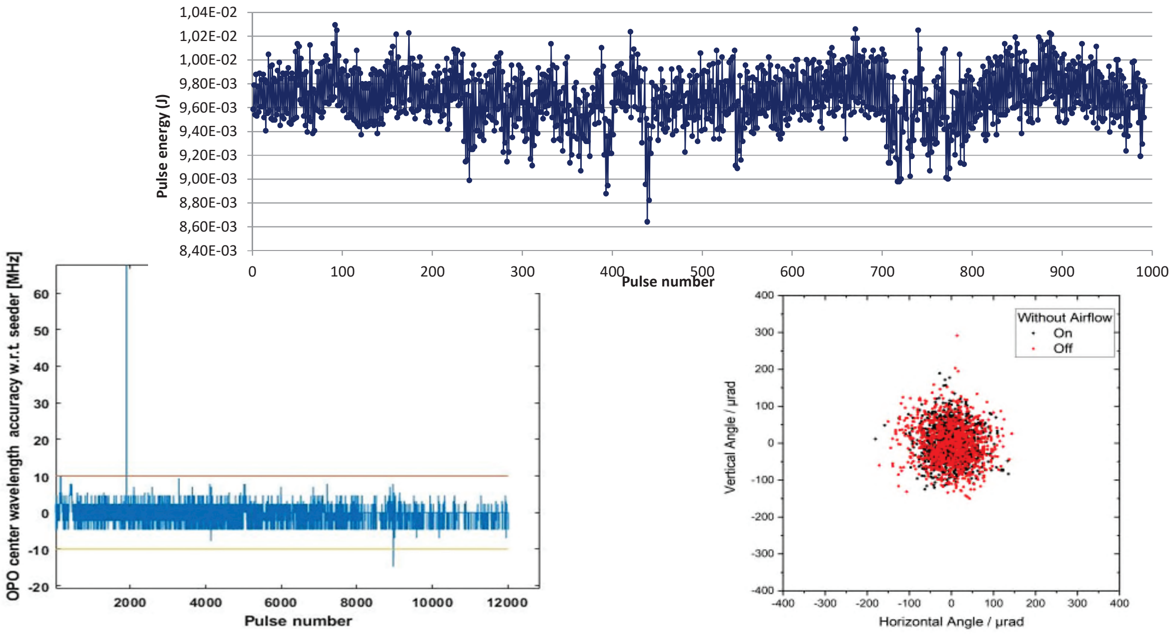

Figure 5: Critical performance results from TxA-BB campaign

Considering the above, the TxA BB campaign confirmed the engineering design of the MERLIN TxA subsystem and proved that the laser related technologies are transferable and suitable for LIDAR space missions which encompass stringent laser performance stability requirements.

3.3 Optical assembly – component qualifications

The majority of all optical mounts inside the MERLIN laser are of the so called C-Mount type (see fixed OPO mirrors of Figure 8). It's used for e.g. mounting of turning mirrors, cavity mirrors and lenses. Based on that qualified design [5], some further, more specific mounts had been developed and qualified in the frame of MERLIN.

KTP Crystal Mount

The KTP crystal as a nonlinear optical component is the core element of the OPO: it converts the 1064 nm laser pulses emitted by the MOPA section into pulses at the required methane absorption line at ~1645 nm.

Being a transmissive optical element, its thermal stability requirement is only < 100 µrad for the operational temperature range. However, its accurate temperature control, required for efficient conversion and amongst others limiting of the pointing difference between On and Off Wavelength, impeded by the difference in heat dissipation of its top and bottom heat sink, in combination with the vibrational loads to withstand, are a challenge of its own. In especial for a design to follow the MERLIN no-organics design rule.

Despite the challenging and competing design goals the KTP mount (see Figure 6) was finally qualified by ILT in 2021. The completely soldered KTP mount is not only a MERLIN specific solution, but also a blueprint for other laser applications requiring the mounting of a nonlinear optical element with high thermomechanical stability and free of outgassing materials. This is of even higher importance for UV laser systems, as like e.g. the AEOLUS 2 mission currently in preparation [8].

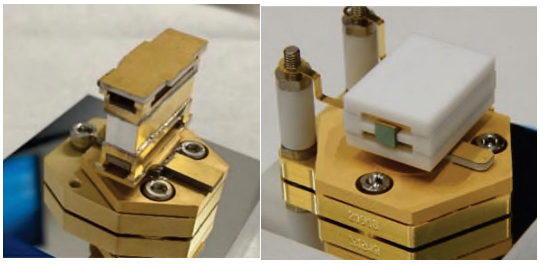

Figure 6: KTP mount (left), PC mount (right)

Pockels Cell Mount

When pulsed laser operation is required, the Q-switch is the one of the crucial element in the Nd:YAG oscillator. Due to the laser crystal's high gain and the therefore required high contrast ratio of the Q-switch, an electro-optical switch is the option to choose. Since ILT is very experienced with BBO Pockels Cells, as already used for FULAS and in various industrial applications, this concept is preferred for the MERLIN laser as well (Figure 6).

While the tilting stability requirement is < 100 µrad as for most transmissive optical elements, the mounting of the extremely brittle BBO material is the main challenge if the use of glue or any other soft organics is not an option. The BBO crystal is soldered directly to the electrodes, which are then soldered inside a ceramic housing.

The MERLIN Pockels cell design was qualified by ILT in early 2022. Since BBO crystals are also suitable for the operation of high-power oscillators, the mount technology can be used for versatile applications with high stability and – due to its organic-free design – long lifetime requirements.

Piezo-driven Mirror Mount

The piezo-driven mirror mount is the core element of the OPO resonator when it comes to the frequency stabilization of the cavity. Here the main challenge is to achieve the required tilting stability < 10 µrad over its full travel range and whole operational temperature range with respect to its initial alignment before launch loads (i.e. shock, vibration and non-operational temperature cycle). The qualification and accelerated lifetime tests have been accomplished in 2021.

3.4 Optical assembly – subassembly qualifications

Pump Module for amplifier stage

The pump module of the amplifier stage hosts two diode stacks for the pumping of the slab amplifier crystal. It has to fulfill a multitude of functions: provide the high current required for driving the stacks, dissipate the heat generated by them and combine the beam lines of both stacks. It also houses the first beam shaping lens of the whole optical pump assembly. Additionally, the stability criteria with respect to environmental loads have to be met while thermally decoupling the biggest heat source of LASO from the baseplate. The EQM pump module was successfully acceptance-tested in early 2022 and has been assembled in the amplifier stage. Currently, the amplifier stage is being further equipped with necessary beam shaping optics to match the pump profile to the amplifier crystal's slab geometry.

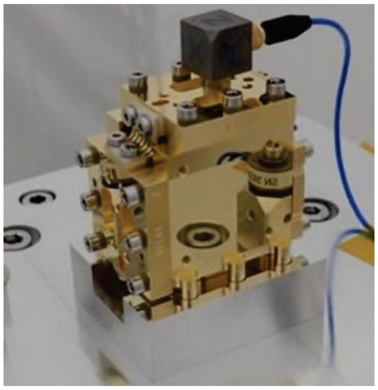

Figure 7: Amplifier pump module during vibrational testing (incl. top mounted test purpose acceleration sensor)

OPO

While the fundamental design and technologies of the laser system and its components had been demonstrated already with the FULAS laser [6], the OPO subassembly is the most important MERLIN specific technological novelty [4]. The basic design was established by DLR IPA [9] for airborne operation, then significantly enhanced in its efficiency and finally thermo-mechanically ruggedized by ILT.

The OPO ring resonator for MERLIN, as shown in Figure 8, comprises of 3 fixed dichroic OPO resonator mirrors (C-Mount design with FULAS and OPTOMECH heritage), a rugged Piezo actuator carrying the 4th resonator mirror for frequency-stabilized operation, and 2 KTP mounts including temperature control of the nonlinear KTP crystals, required for generating the desired scientific wavelengths of ~1645 nm. The OPO subassembly is mounted on a separate baseplate which will in a later AIT stage be mounted on the laser bench. The qualification of the C-mounts for the mirrors was accomplished in the frame of the OPTOMECH program [5], while the KTP mounts and the Piezo mount were qualified within the MERLIN project. The OPO acceptance campaign was successfully performed in early 2022, demonstrating the high thermomechanical stability at subassembly and component level. The OPO optical performance showed no signs of degradation (energy output, pointing, spectral stability) after the environmental campaign.

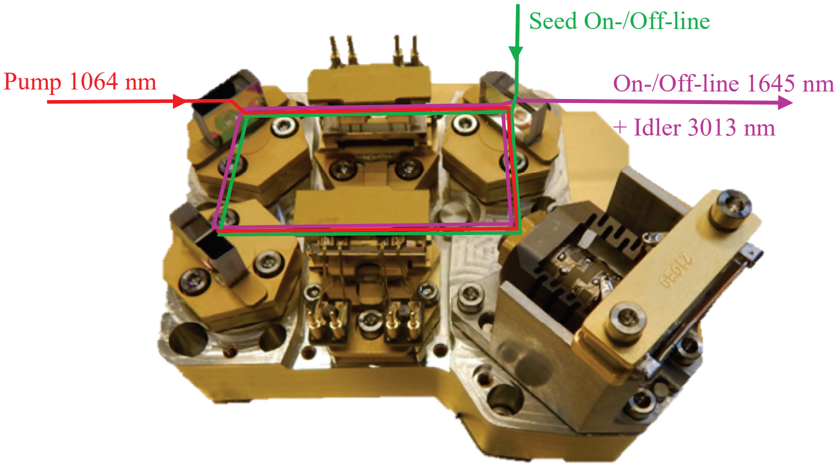

Figure 8: MERLIN Laser OPO subassembly with 3 fixed and 1 piezo driven mirrors and 2 thermal controlled KTP mounts

4. . CONCLUSIONS

The underlying design of the MERLIN laser has proven its outstanding thermomechanical performance in the frame of the FULAS project. The long-lifetime potential is given by the low-outgassing concept of the whole laser and harness, implemented in a pressurized and hermetic housing. Through the TxA BB campaign the engineering design of the MERLIN TxA subsystem could be demonstrated, meeting all performance stability goals which enable high measurement precision for the instrument [7]. With the accomplished component and subassembly qualifications, the MERLIN TxA technology is showing its maturity and flightworthiness. The accomplished performances justify the laser design’s thermomechanical robustness and its suitability for other future LIDAR missions featuring high power lasers [8].

5. ACKNOWLEDGEMENTS

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