

Adaptation of the laser transmitter engineering model designed according to the Aeolus-2 specifications to a pump source for a Water Vapour LIDAR

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ABSTRACT

For ESA's Aeolus-2 mission, Fraunhofer ILT and Airbus Defense & Space Germany have designed an engineering model (EM) of a reliable pulsed single-frequency laser source. It is designed to deliver pulses of > 400 mJ energy, 30 ns duration, at 1,064 nm and 50 Hz pulse repetition frequency (PRF), pumping a frequency conversion unit to generate > 150 mJ at 355 nm. The laser is a master oscillator power amplifier (MOPA) with a diode-pumped Nd:YAG oscillator and two INNOSLAB amplifiers. After oscillator integration, the project scope changed, and the EM is now supposed to serve as the 1,064 nm pump source for a frequency converter breadboard within ESA's QLEO activities, aimed at generating single-frequency pulses at 935 nm for water-vapour detection. QLEO requires > 300 mJ pump energy at a PRF of at least 100 Hz, preferably 200 Hz. This roughly doubles the average IR power and the thermal load compared to the original design.

The opto-mechanical design allows flexible operating points even at double or higher PRF. The oscillator, which had already been integrated and tested for 50 Hz PRF, was operated and characterised at 100 Hz whilst maintaining the same pump pulse energy, with the thermal load doubled. When the PRF was doubled, the pulse energy and beam quality remained virtually constant, neither the oscillator had to be readjusted nor a control parameter had to be modified. In the INNOSLAB concept, the laser mode matches the pump mode in the amplifier crystals, ensuring high efficiency and good beam quality. Stronger thermal lenses in the crystals alter amplifier resonator modes, but this is easily compensated by adjusting beam-shaping telescopes. The amplifier pumps can operate at twice the PRF with a manageable wavelength shift.

The limiting factor for the average power of this laser is heat dissipation. Once the setup of all the optical components has been completed, a passive Thermal Control System (TCS) will be integrated: the residual heat will be conducted via copper-water heat pipes (CWHP) to a thermal interface. Components must stay within dedicated temperature ranges, so CWHPs are tailored to each component considering heat loads, routing constraints, operating temperature, and microgravity. An in-house soldering process provides reliable, reproducible connections. Cascaded CWHP assemblies allow stable thermal links over distances beyond intrinsic length limits. The TCS is originally designed for 50 Hz operation according to Aeolus-2 requirements. Now it must dissipate a correspondingly greater heat load so that the laser can meet the QLEO requirements.

Keywords: Laser, LIDAR, space, optics, INNOSLAB, Aeolus, QLEO, Heat Pipe

1. INTRODUCTION

At ICSO 2022 and ICSO 2024 we reported on the design, verification and assembly, integration, and testing (AIT) of an Engineering Model (EM) for the laser transmitter assembly (LTA) for the Aeolus-2 mission [1, 2]. The laser is designed as an electro-optically Q-switched, single-frequency seeded oscillator followed by two INNOSLAB amplifiers [3] and a frequency tripling unit. Its goal was to generate pulses with more than 150 mJ energy and approximately 30 ns pulse duration at a wavelength of 355 nm, pulse repetition frequency (PRF) of 50 Hz and a beam quality of $M^2 < 2$.

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The optomechanical components are mounted on a monolithic baseplate, which is equipped from both sides and isostatically mounted inside the laser housing, which in turn is designed for isostatic platform mounting. Optics are adjusted in molten solder using piezo-driven hexapods, achieving sub-micrometer precision and thermomechanical stability of about 10 μ rad for set-and-forget mounting. This technology has been developed by ILT and Airbus within the OPTOMECH projects funded by the German Aerospace Administration (DLR) [4, 5]. The laser housing is hermetically sealed and pressurized, using almost no organic materials to avoid laser-induced contamination, with flux-free soldering, ceramic boards, and ceramic insulation. For thermal management, pump diodes, laser crystals, and frequency-conversion components are thermally decoupled from the baseplate and housing; waste heat is conducted directly via copper-water heat pipes to a thermal interface, then out of the housing, ensuring minimal temperature gradients and high stability.

The optical concept was verified using an optically fully representative Aeolus-2 Breadboard (BB), which was originally developed to investigate and demonstrate the further scaling of pulse energy based on the INNOSLAB design [4]. The requirements resulted from the DLR-funded Aeolus Follow-On study conducted by Airbus Defence and Space Germany. This study was a collaborative effort involving the laser team at Airbus Defence & Space Germany and ILT, the Aeolus instrument team at Airbus Defence & Space France, and members of the Aeolus Science Advisory Group acting as consultants.

The laser consists of a Nd:YAG oscillator and a Nd:YAG INNOSLAB amplifier, delivering approximately 85 mJ pulse energy, followed by a scaled INNOSLAB power amplifier. This MOPA configuration generates single-frequency pulses with energies of up to 525 mJ at a PRF of 100 Hz and a pulse duration of approximately 30 ns. The overall optical-to-optical efficiency is 23 %. The beam quality factors are $M^2_x=1.8 / M^2_y=1.4$. To prevent parasitic lasing caused by coupling between the two amplifier stages, they are separated by Faraday isolators. A schematic of the Aeolus-2 BB setup is shown in Figure 1. The breadboard fully meets the optical specifications of the Aeolus-2 LTA. Its PRF of 100 Hz even exceeds the Aeolus-2 requirement by a factor of two. Hence, the Aeolus-2 LTA EM has been designed accordingly, with the Aeolus-2 BB being optically fully representative.

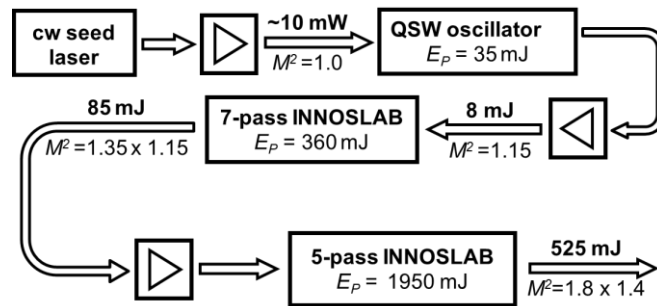


Figure 1. Optical architecture of the Aeolus-2 BB and the Aeolus-2 LTA EM

Within validation experiments with the Aeolus-2 BB UV pulse energies of 180 mJ at of 100 Hz PRF have been demonstrated. The conversion efficiency from infrared (IR) to UV reached 43 %, and the beam quality was nearly diffraction-limited. Due to the good conversion efficiency of 43 % from the IR to the UV, only 420 mJ IR pulses were required which secures a high performance margin for aging and/or potential performance upgrade. Since a critical factor for long system lifetime is the limitation of UV fluence, the converter has been designed with a maximum peak fluence of < 1 J/cm² to be optimised for a long lifetime and to meet the Aeolus-2 requirements. Additionally, a ten-day continuous operation test was conducted. Because the PRF during the test is doubled compared to the Aeolus-2 requirements, this corresponds to a 20-day test under actual Aeolus-2 conditions. Despite unfavorable ambient conditions regarding lab temperature stability, the test showed excellent pulse energy and conversion efficiency stability, with all parameters remaining within the Aeolus-2 requirements. Importantly, no signs of Laser-Induced Contamination (LIC) were detected after the endurance test, confirming the reliability of the optical concept [2].

The thermomechanical concept was verified with the optomechanically representative FULAS laser, the first laser demonstrator set up by ILT and Airbus using the OPTOMECH technology [7, 8]. This laser was subjected to thermal stress levels that exceeded the expected Aeolus-2 conditions by far. Remarkably, the FULAS laser remained fully within

the Aeolus-2 specifications during these demanding tests, without any need for adjustments or modifications [2]. This success highlights the robustness of the space-qualified OPTOMECH components. These same components are utilised to set up the oscillator and the first amplifier of the Aeolus-2 EM. For the second amplifier, the design of these qualified components has been scaled up. Their thermomechanical properties were first analysed using the Finite Element Method (FEM). These theoretical analyses were then experimentally confirmed by assembling one type of the scaled optomechanical mounts and subjecting it to both thermal and mechanical qualification tests under Aeolus-2 conditions. The mounts passed all qualification tests with sufficient margin [2].

The Thermal Control System (TCS) of the Aeolus-2 LTA EM is designed to remove up to 300 W of dissipated heat from multiple opto-mechanical assemblies while maintaining component-specific operating temperatures under strict mass, volume, contamination, and reliability constraints. The laser incorporates fifteen distributed thermal interfaces associated with pump modules, laser crystals, and other and other components from which heat needs to be dissipated. These heat sources must be thermally coupled to a common instrument cold plate over distances of up to several hundred millimeters within a densely packed optical architecture. Conventional solutions such as solid metallic conductors, graphite-based elements, active liquid cooling systems, or loop heat pipes were evaluated but could not simultaneously satisfy the requirements regarding passive operation, geometric flexibility, contamination control, mass restrictions and integration complexity. Consequently, copper–water heat pipes (CWHPs) were selected as the primary heat transport technology for the EM.

The flight-representative Aeolus-2 EM oscillator, including its seeding unit, has been fully set up and thoroughly characterized (results see section 3). The two pumps for the first amplifier, comprising two diode laser stacks each including beam shaping and homogenisation optics, had been successfully assembled and integrated. In summary, the results prove the general suitability of the optical, optomechanical, and thermomechanical concepts for space operations. This proven robustness and modularity make this technology a promising candidate for future spaceborne laser LIDAR applications. The successful test results and the smooth integration of the EM underline the maturity and reliability of the system design for the demanding space environment.

2. USING THE AEOLUS-2 LTA EM AS A PUMP SOURCE FOR QLEO

Since ICSO 2024, the objectives for the laser's use have changed, as it is no longer required as a demonstrator for an Aeolus-2 LTA. However, the laser's infrared component is ideally suited to pumping the frequency conversion unit for the QLEO mission which is proposed for ESA's Earth Explorer 12 programme. The QLEO mission will be an active remote sensing mission carrying a single payload: a differential absorption LIDAR operating near 935 nm to measure water-vapor profiles. Its primary objective is to retrieve vertical profiles of tropospheric water vapor in both clear and cloudy conditions, including assessments of the planetary boundary layer's depth, structure, and moisture content. In addition, QLEO aims to capture vertical profiles of tropospheric aerosols and to estimate aerosol optical depth, thereby improving our understanding of aerosol distribution. The mission also focuses on identifying cloud boundaries, specifically the tops and, where detectable, the bases of high- and mid-level clouds, and on measuring the optical depth of cirrus and thin mid-level clouds. The key parameters for the QLEO transmitter output are listed in Table 1¹.

¹ Statement of Work of ESA's Invitation to Tender AO/1-12831/25/NL/SC

Table 1. Main requirements for QLEO transmitter output

	ESA requirement
Pulse energy	> 70 mJ
Pulse repetition frequency	≥ 100 Hz, preferably up to 200 Hz
Wavelength	four dedicated wavelengths in the range 935 nm – 936 nm
Pulse duration	< 200 ns
Spectral bandwidth	< 160 MHz (FWHM)
Spectral stability	< 60 MHz (RMS)
Beam propagation factor	$M^2 < 3$
optical-to-optical conversion efficiency 1,064 nm → 935 nm	> 25 %

These values can be achieved in various ways. Firstly, they can in principle be generated directly using a customised crystal (Neodymium-doped Yttrium Lutetium Gallium Garnet (Nd:YLuGG)) [9], which can be pumped at a wavelength of around 808 nm. However, some properties of the crystal make it difficult or impossible to meet the QLEO requirements. Its emission cross section at 935 nm is $1.9 \times 10^{-20} \text{ cm}^2$, which means that it has almost fifteen times greater saturation fluence than Nd:YAG (emission cross section: $28 \times 10^{-20} \text{ cm}^2$). Significantly higher fluences are therefore required for efficient operation. In addition, Nd:YLuGG has its greatest amplification at 1,062 nm with an emission cross section of $12.9 \times 10^{-20} \text{ cm}^2$. The optical coatings must be designed accordingly to suppress parasitic oscillation at 1,062 nm, which makes the coatings more complex than for Nd:YAG and lowers the damage thresholds accordingly. These characteristics, which are disadvantageous for space applications, result in a conflict of objectives that cannot be resolved within the framework of the QLEO requirements.

The 935 nm wavelength can also be achieved using Ti:sapphire. Ti:Sapphire exhibits a broad gain bandwidth, with its maximum gain centered around 800 nm; the wavelength of 935 nm also falls within this gain band. Its absorption band is similarly broad, peaking in the green spectral region. Therefore, a frequency-doubled Nd:YAG laser emitting at 532 nm would be the natural pump source, particularly when taking space-qualification constraints into account. Prior work on this concept has demonstrated conversion efficiencies from 532 nm to 935 nm of up to 22 % [10]. The Aeolus-2 BB has an optical efficiency of 22 % as well [4]. With an SHG conversion efficiency between 70 % and 80 % and a wall-plug efficiency of 50 % for the pump diodes, the overall efficiency of the Ti:Sapphire laser would be below 2 %.

At 935 nm, the emission cross-section of Ti:Sapphire is less than $20 \times 10^{-20} \text{ cm}^2$ for p-polarization and less than $10 \times 10^{-20} \text{ cm}^2$ for s-polarization. For comparison, Nd:YAG has an emission cross-section of $28 \times 10^{-20} \text{ cm}^2$ at 1064 nm. Consequently, the saturation fluence of Ti:Sapphire is two to three times higher than that of Nd:YAG. For spaceborne applications the fluence on the Nd:YAG amplifier crystals should be kept below 3 J/cm² to maximise operational lifetime. Owing to the favourable properties of Nd:YAG, good energy extraction and correspondingly high efficiencies are achievable at this fluence. For Ti:Sapphire, however, the fluence would need to be two to three times higher to reach similar efficiencies, which would impose significantly greater stress on the optical coatings compared with Nd:YAG. Furthermore, relative to an Nd:YAG laser, the coatings on Ti:Sapphire crystals must have a broader bandwidth to suppress parasitic oscillations near the gain peak at approximately 800 nm, and the mirrors must be anti-reflective for the same reason. These additional requirements make the coatings more complex and reduce their damage threshold. The result is a similar trade-off for Ti:Sapphire, which is almost impossible or entirely impossible to resolve, as is the case for Nd:YLuGG.

For these reasons, and particularly in view of the need for space-qualification, it seems more sensible to achieve the values at 935 nm using an SHG/OPO/OPA setup pumped by a pulsed Nd:YAG laser. Given the specified optical-to-optical efficiency of 25 %, Nd:YAG pulses of > 280 mJ at a wavelength of 1,064 nm are required. Such laser beam sources have been developed as part of the Aeolus-2 activities and are therefore, in principle, available. Compared with the solutions mentioned above, the TRL of these pump lasers is comparatively high. Accordingly, ESA is taking this approach for the QLEO mission. The specifications for the pump laser are listed in Table 2.

Table 2. ESA requirements for the Nd:YAG pump laser beam source

	ESA requirement
Pulse energy	> 300 mJ
shot-to-shot pulse energy stability	< 2 % (RMS)
Pulse repetition frequency	≥ 100 Hz
Wavelength	1,064 nm
Spectral bandwidth	single frequency operation
Spectral stability	< 50 MHz (RMS)
Beam propagation factor	$M^2 < 2$

These parameters – in particular the PRF of 100 Hz – match perfectly with the parameters that ILT demonstrated with the Aeolus-2-BB already in 2017. Before it was used for the validation of the Aeolus-2 LTA EM in 2023, it was used for pumping an OPO/OPA stage to convert the wavelength to 1,645 nm [11], which is used for CH₄ detection in the CHARM-F and MERLIN missions [12, 13]. In this configuration, the breadboard was operated on a daily basis for more than one year to perform LIDT testing for MERLIN at both 1,064 nm and 1,645 nm. The suitability of the breadboard as a pump source for a frequency-conversion unit has therefore already been demonstrated.

ILT is currently developing a QLEO breadboard (QLEO BB) in collaboration with Airbus Defence & Space and RUPHOS GmbH, with the aim of demonstrating the optical specifications for the QLEO mission [14]. It consists of a frequency doubler to convert the pump laser beam to a wavelength of 532 nm and an OPO/OPA assembly. The modelling calculations for the QLEO BB suggest that, in the best-case scenario, the conversion efficiency from 532 nm to 935 nm could exceed 40 %. Assuming a conversion efficiency from 1,064 nm to 532 nm of over 70 %, the overall efficiency of the QLEO BB would be well above the required 25 %. Consequently, the pump laser could be operated at a reduced pulse energy, which would reduce the thermal load and allow more scope for increasing the PRF. The QLEO BB is currently being pumped by the Aeolus-2 BB. The aims of the experiments are to test and validate its optical design, determine its conversion efficiency and thus the most favourable operating point for the pump laser in terms of pulse energy and beam parameters. These experiments will subsequently be validated using the modified Aeolus-2 LTA EM.

In order for the Aeolus-2 LTA EM to serve as a pump source for the QLEO, it must be operated at a frequency of at least 100 Hz, even though it was designed for only 50 Hz. With the same pulse energy, doubling the PRF results in almost exactly double the thermal load. Consequently, the greatest challenge lies in heat dissipation. Admittedly, the packages housing the heat-generating components – essentially the pump diodes and the laser crystals – are designed to handle significantly greater thermal loads than those that would arise in Aeolus-2. In principle, any amount of heat which this optical setup is capable of can be dissipated from the packages by scaling the size and number of heat pipes. However, due to the strict mass and volume constraints in the Aeolus-2 specifications, the CWHF based TCS – designed for 50 Hz – has not been oversized. Some components could quite easily be fitted with larger or additional CWHFs, whilst there is insufficient space on other components to do so. Although a mechanical redesign to allow larger CWHFs to be fitted in these locations would, in principle, be possible, however, within the scope of this project this cannot be realised due to time and budget constraints. Therefore, we have to work with the designed TCS and can only choose the best-performing heat pipes.

The pulse energy may possibly be reduced slightly: the EM was designed for > 150 mJ in the UV, and in the validation experiments we demonstrated the 150 mJ with a pump pulse energy of 350 mJ. The TCS was dimensioned accordingly. However, the pulse energy required for QLEO could be lower, provided the optical-to-optical efficiency of > 25 % according to the results of the QLEO BB's optical modelling is achieved [14]. This would reduce the thermal load somewhat but would also entail a slight loss of efficiency: in the INNOSLAB principle, the laser mode and the pump modes are matched to one another. This ensures high efficiency and good beam quality, as virtually no gain region is wasted. The amplifier cavity and the size of the pumped region in the INNOSLAB crystal are matched to the emission cross-section of the gain medium in such a way that the amplifier is operated in a saturated state for maximum energy efficiency, whilst the fluence is maintained at a maximum value determined by the gain material and the application, in order to ensure the longest possible laser lifetime. In principle, if the pulse energy were to be reduced, the amplifier would need to be redesigned so that it could operate at the same optimised operating point, using correspondingly smaller beam

diameters to maintain the same fluence. However, this is not possible in the scope of this project due to time and budget constraints.

In the Aeolus-2 LTA EM, the design fluence was 3 mJ/cm². The saturation fluence of Nd:YAG at a wavelength of 1,064 nm is approximately 0.7 J/cm². Accordingly, even if the pulse energy were halved – which, with the amplifier resonator design remaining unchanged, would result in the fluence being halved – the amplifier would still be operating at more than twice the saturation fluence. If, in practice, the laser is actually operated at a lower pulse energy, only a negligible loss of efficiency would be expected.

The change in thermal load within the INNOSLAB amplifiers, caused by the change in operating point, results in a change to the thermal lens and, consequently, to the resonator geometry of the amplifiers. However, this change can be easily compensated for by adjusting the beam-shaping telescopes between the oscillator and the first amplifier, and between the first and second amplifiers. A redesign is not required.

The oscillator is not affected by these considerations: ideally, its pulse energy should not be reduced so that the first amplifier can operate as efficiently as possible. Accordingly, doubling the PRF would mean doubling the thermal load and thus the thermal lens in the oscillator crystal. However, the resonator is designed not only to remain stable over a very wide bandwidth of the thermal lens, but also to ensure that the beam size within the crystal remains virtually unchanged. In this respect, doubling the thermal load is expected to result in only a minor loss of beam quality, which is acceptable in this context.

As the oscillator contributes only 2 % - 3 % to the laser's total thermal load, the additional load on the TCS resulting from the doubling of its PRF is completely negligible, and the heat pipes for the oscillator are, in any case, far from reaching their capacity limit.

3. RESULTS OF THE OSCILLATOR CHARACTERISATION

During the integration of the oscillator, 50 Hz operation was still assumed. Accordingly, the operating point was set to a pulse energy of approximately 8 mJ to 9 mJ at a 50 Hz PRF. The integration process utilises thermal ground support equipment (TGSE), consisting of water-cooled metal heat sinks that can be attached to each component. The heat sinks have an integrated heating cartridge, enabling the temperature of the individual components to be precisely controlled and varied over a wide range, thereby enabling characterisation of the temperature sensitivity of the individual components. Consequently, it is possible to determine the temperature-dependent performance of each component, which ultimately helps to precisely define the requirements for the flight TCS. After integration of the oscillator the operating point has been changed to 8 mJ to 9 mJ at a PRF of 100 Hz. Accordingly, a detailed characterisation of the oscillator, including temperature variations, was initially carried out at 50 Hz.

The oscillator was first tested in quasi-CW mode. The characteristic curves for power versus current were measured at 50 Hz and 100 Hz. Around the design operating point of 70 A, the characteristic curves are almost linear. The difference in slope between the power characteristics is almost exactly a factor of 2, and the pulse energy characteristics are virtually identical. The characteristics show that the oscillator is being operated well within its stability limits. In buffered single-frequency operation at 50 Hz PRF, a similar picture emerges with regard to the linearity of the characteristic curve. At the operating point, a pulse energy of > 9 mJ is achieved; the beam diffraction number, measured using the 4-sigma method, is $M^2 < 1.2$, which also remains constant over a wide range around the operating point (Figure 2).

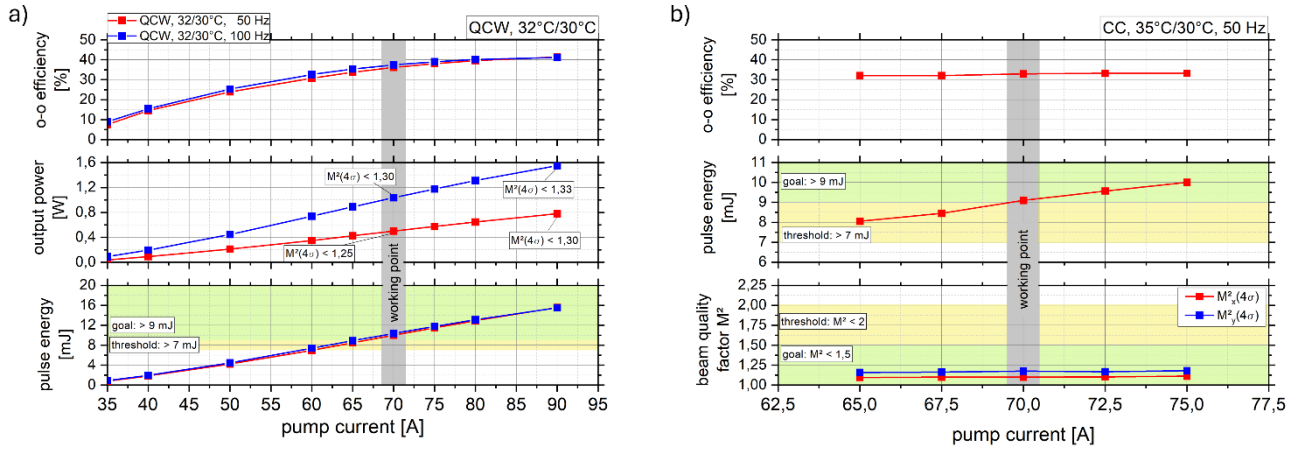


Figure 2. a) Current-power characteristic curves in quasi-continuous wave (quasi-CW) operation at 50 Hz and 100 Hz. The characteristic curves are virtually linear well beyond the operating point, demonstrating the large margin. The pulse energies (quasi-CW output energy per pump pulse) are the same for both 50 Hz and 100 Hz operation. No parameters other than the current and trigger frequency were altered. b) Pulse energy characteristic curve showing beam quality and optical-to-optical efficiency in pulsed single-frequency operation.

The temperatures of the pump diodes and the laser crystal were varied independently of one another, and the corresponding characteristics were measured. The operating point for the crystal temperature is 30 °C; the pulse energy and beam quality were measured in the temperature range from 24 °C to 36 °C at a PRF of 50 Hz. Both parameters remain virtually constant across the entire temperature range. The temperature of the pump diodes at the operating point is 35 °C; pulse energy and beam quality were measured over the temperature range from 28 °C to 40 °C. As the laser diodes are not spectrally stabilised, they undergo a wavelength shift during temperature variation, which has a slightly greater influence on the pulse energy than the variation in crystal temperature: The pulse energy varies between 8.5 mJ and 9.5 mJ across this temperature range. However, even the lowest pulse energy measured within this temperature range is sufficient to drive the amplifier chain; accordingly, the impact on the overall laser system would be marginal (Figure 3).

To check whether a temperature-induced loss of pulse energy could be compensated for without causing other problems, the pump current was increased at the pulse energy minima within the temperature range of 12 K around the working point to such an extent that the pulse energy equaled that at the maximum of the temperature range: at both minima, the temperature-induced drop in pulse energy could be compensated for with a slight increase in pump energy. The beam quality, which did not change measurably across the entire temperature range at nominal current, also remained virtually constant during this compensation (Figure 3).

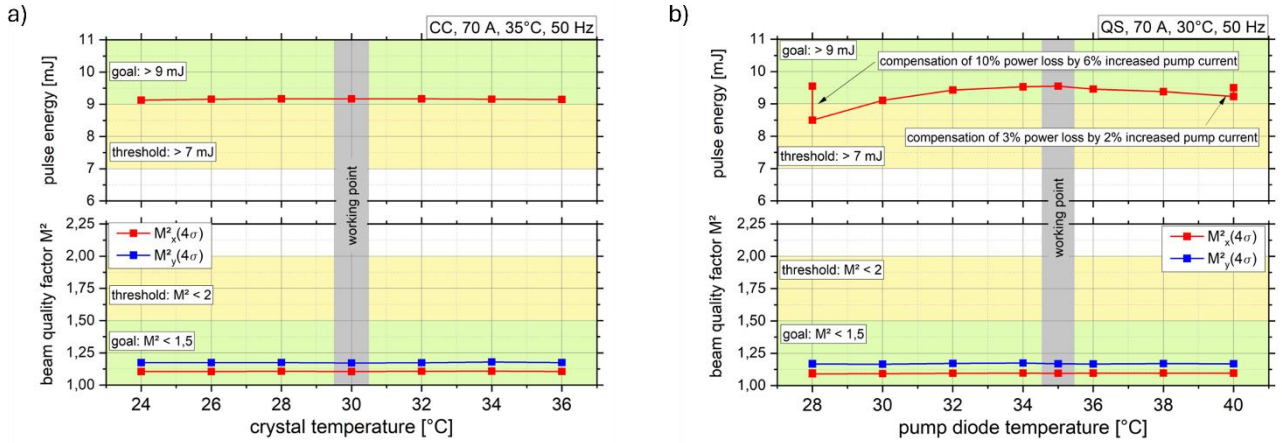


Figure 3. a) Variation in crystal temperature during 50 Hz operation: Pulse energy and beam quality remain virtually constant over a temperature range of 12 K. b) Variation in pump diode temperature during 50 Hz operation: Beam quality remains virtually constant over a temperature range of 12 K. The pulse energy always remains above the saturation threshold for the amplifier chain. Any temperature-induced deviation in pulse energy can be compensated for by varying the pump current without any loss of beam quality.

The warm-up behaviour of the oscillator was investigated: the cooling water temperature for the oscillator components was 25.5 °C during integration. The operating temperature of the crystal is 30 °C, whilst that of the pump diodes is 35 °C. In an initial test, the heating elements were switched on, and the oscillator was switched on as soon as the last component (in this case the pump diodes) was within a temperature range of ± 0.5 °C of the operating point, which occurred after approximately 5 minutes. The oscillator was almost at the operating point from the very first pulse: it started with approximately 1.4 % less pulse energy than the average achieved in steady state (9.4 mJ). This means that, as soon as the components have reached operating temperature, the oscillator generates sufficient pulse energy to saturate the amplifier chain. In a second test, the oscillator was started simultaneously with the heating cartridges from a state of thermal equilibrium at laboratory temperature and a cooling water temperature of 25.5 °C, and the pulse energy was measured. The result shows that the pulse energy curve over time follows the temperature curve of the pump diodes. After approximately 90 seconds, a pulse energy of > 9 mJ is reached (Figure 4).

Both tests show that the oscillator's performance depends almost exclusively on the crystal and pump diode temperatures. No thermal stabilisation of the optomechanics is required, as the vast majority of the waste heat is dissipated directly from the components to the TCS. Only a very small fraction is coupled into the baseplate, but the resulting temperature gradients are so small that they have no effect on the oscillator's performance.

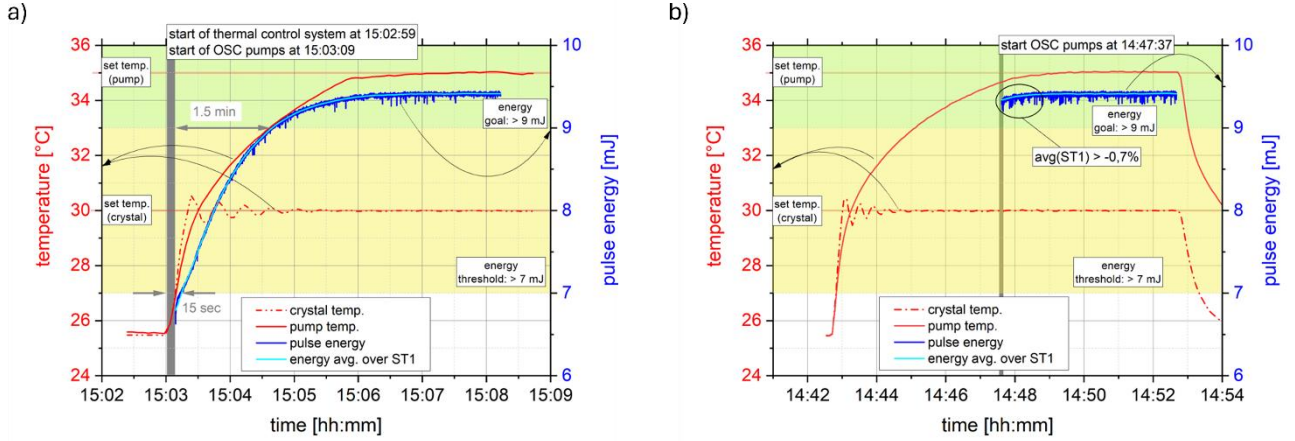


Figure 4. Start-up behaviour of the oscillator: (a) without thermally stabilised components; (b) with thermally stabilised components. As waste heat is coupled directly into the TCS, there is no need to thermally stabilise the optomechanical mounts or the baseplate in order to achieve full oscillator performance, provided that these are already in thermal equilibrium with the environment.

To test the oscillator's sensitivity with regard to PRF and, consequently, thermal load, the oscillator's performance in terms of pulse energy, average power and beam quality was measured at an operating point of 70 A in Q-switched mode at various PRFs in the range from 50 Hz to 100 Hz. The results show that the pulse energy remains constant at > 9.4 mJ, which is confirmed by the measurement of the average power: this increases linearly with the PRF from 473 mJ at 50 Hz to 950 mJ at 100 Hz. The beam quality also remains virtually constant at $M^2 < 1.25$ (only slight degradation: M^2_x from 1.1 to 1.13, M^2_y from 1.17 to 1.22). The characterisation curves are very linear across the entire PRF range and show no signs of cut-off, which demonstrates that the oscillator is very stable across the entire range and has considerable headroom.

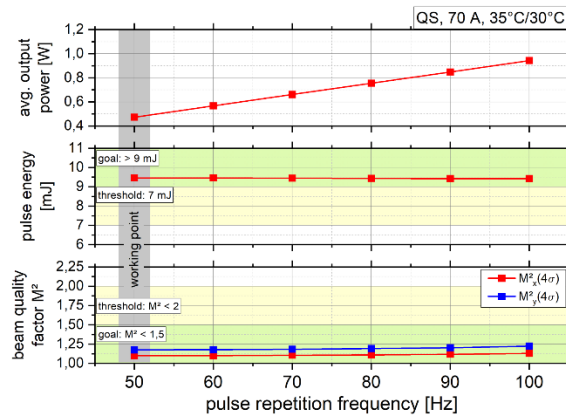


Figure 5. Performance of the oscillator with respect to the PRF. Pulse energy and beam quality remain virtually unchanged, demonstrating the oscillator's high stability

The beam pointing stability was measured in the Fourier plane of a 400 mm lens using a CCD camera. The centroid position of the transverse beam intensity distribution is measured over time. The temperature of the laser crystal was maintained at a constant 30 °C. The diode temperatures varied between 28 °C, 30 °C and 35 °C; in addition, at a diode temperature of 35 °C, the PRF was set to 70 Hz and 100 Hz. From the original operating point (50 Hz, 35 °C diode temperature), the pointing difference in each of the selected parameter sets was < 10 μ rad. For each parameter set mentioned, the pointing was measured over 1 minute. The pointing fluctuations around the mean value were < 3 μ rad for each parameter set. This value is > 10 times better than our design target, which is defined as the pointing deviation that

causes a 1 % power loss in the AMP1. The pointing measurements were carried out with the laser housing open under a flow box. Accordingly, significantly smaller pointing values can be expected once the laser is enclosed and no longer exposed to the air movements within the flow box.

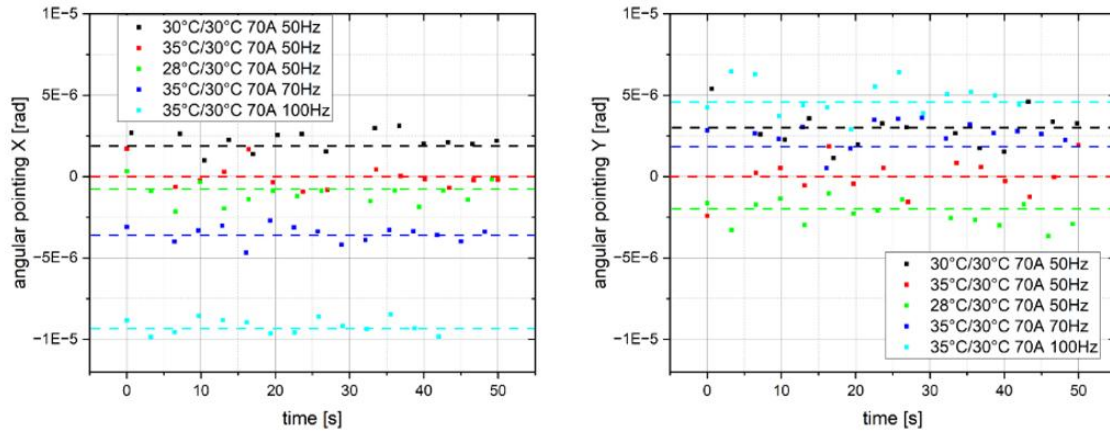


Figure 6. Pointing measurements at various temperatures, each lasting approximately one minute.

The other key oscillator parameters are also virtually independent of the PRF: the pulse duration is 26 ns, the spectral linewidth is 17.9 MHz, the frequency stability using the ramp-fire method for single frequency stabilisation [15] is 0.45 MHz (rms over 14 s), the degree of polarisation is > 23.7 dB, and the short-term energy stability (rms over 14 s) is < 0.13 %. The results are excellent in terms of efficiency, beam quality, spectral bandwidth, and stability of output parameters. The oscillator demonstrated exceptional robustness across a wide range of input parameter variations, including changes in pulse repetition frequency and the temperature of both pump diodes and the laser crystal, exceeding the Aeolus-2 stability requirements by far. The results of the characterisation indicate that the oscillator can be operated without any problems at 100 Hz as well as at 50 Hz, without the need for any adjustment or changes to any control parameters.

4. AMPLIFIER PUMPS

Both INNOSLAB amplifiers are pumped on both sides; accordingly, each amplifier is equipped with two identical pumps. The optical design for the pumps in both amplifiers is identical; the pumps for the second amplifier are a scaled version of those for the first amplifier. The pumps for the first amplifier are each fitted with two diode laser stacks, whilst the pumps for second amplifier are each fitted with eight stacks. All stacks are identical in design and consist of 8 bars. In both types of pumps, the diode laser stacks are polarisation-coupled in pairs. The diode light is coupled into a homogeniser in the slow direction; the facet of the homogeniser facing the crystal is imaged onto the crystal. The diode light then fills the crystal width in a near-top-hat shape. Homogenisation in the slow direction ensures that varying emitter degradation or, indeed, the failure of individual emitters does not lead to intensity fluctuations across the pump line width. Any loss of power due to failure or degradation can be compensated for by increasing the pump current. In the fast direction, the line height is matched to the amplifier resonator mode. This matching of the pump mode to the laser mode, together with homogenisation in the slow direction, results in the high efficiency and excellent beam quality of the INNOSLAB amplifiers [3].

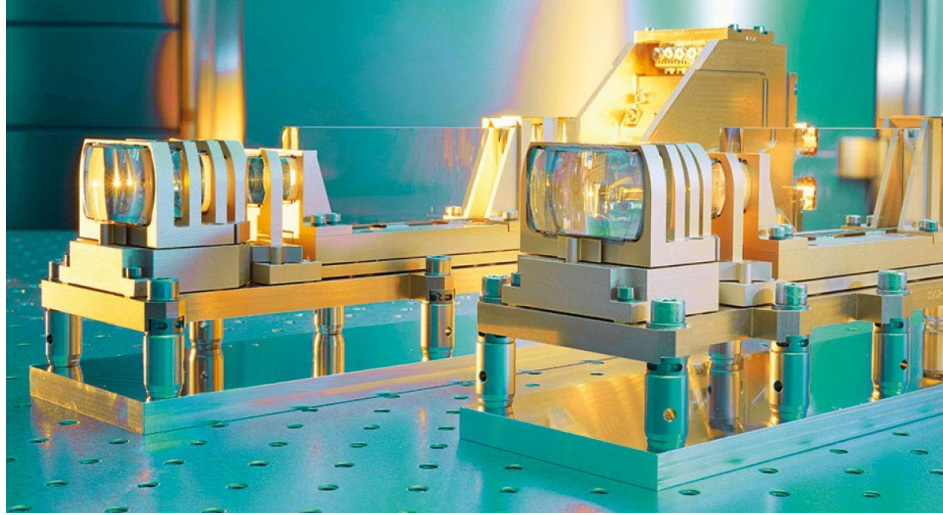


Figure 7. Pumps for the second amplifier; all optical components are soldered into their mounts.

These amplifier pumps were assembled and characterised at 50 Hz and 100 Hz. The pump diodes were cooled by the TGSE whilst the heating element was switched off, with a cooling water temperature of 24 °C. All four pumps behaved identically in terms of power characteristics and wavelength shift; for this reason, only the results for one of the two pumps for the second amplifier with greater heat dissipation are shown here as an example. The transfer efficiency – that is, the ratio of the power in the crystal plane to the power of the diode laser stacks behind the polarization coupling – is 94.2 %. The current-power characteristic of the pump was measured at a pump pulse duration of 160 μ s. Both characteristics at 50 Hz and at 100 Hz are linear with no signs of roll-over. At 130 A, the average power is 48.3 W at 50 Hz and 96.5 W at 100 Hz respectively. The doubling of the power when the PRF is doubled shows that the pump can be operated at twice the PRF without any problems, without the additional heat dissipation causing any misalignment or similar issues at any point in the pump.

The spectral width of the pump is 2.9 nm (FWHM) for both PRFs; the average wavelength at which the intensity is 50 % of the maximum is 804.2 nm at 50 Hz and 805.4 nm at 100 Hz. This wavelength shift of 1.2 nm was expected and can even when the passive TCS is used be compensated for.

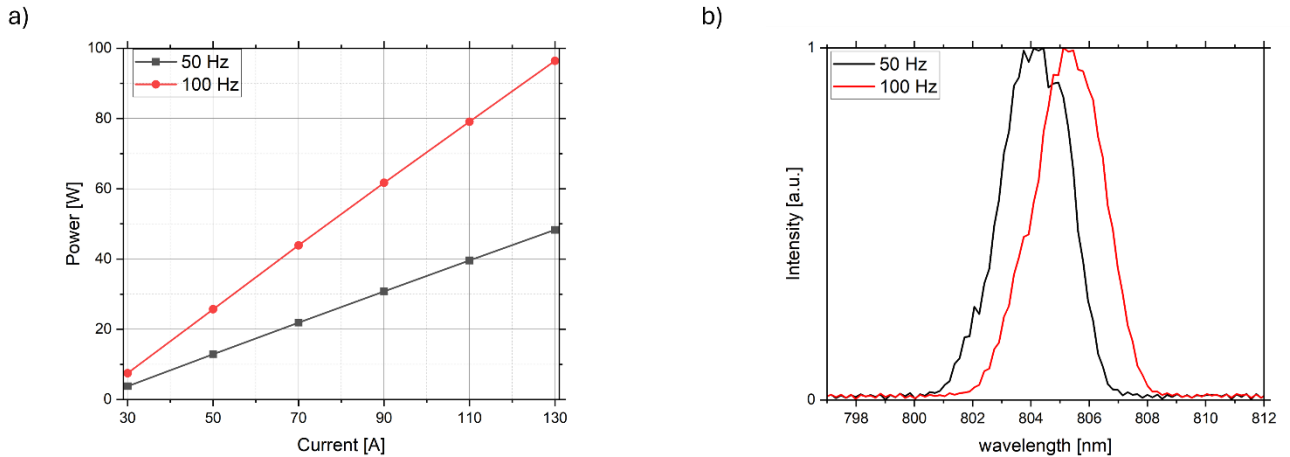


Figure 8. a) Current-Power characteristics for one of the two pumps for the second amplifier at a pump pulse duration of 160 μ s. b) Spectra of the pump at 130 A and a pump pulse duration of 160 μ s.

The results show that the pumps themselves do not exhibit any signs of degradation when operating at double the PRF. Consequently, they can be used for 100 Hz operation without modification.

5. THERMAL MANAGEMENT USING COPPER–WATER HEAT PIPES

CWHPs provide exceptionally high effective thermal conductance while maintaining low mass and a slender form factor that can be routed around optical beam paths and electrical harnesses. Their operation is based on a passive two-phase cycle in which heat applied at the evaporator vaporizes the working fluid, while capillary forces within an internal wick structure return the condensate from the condenser to the evaporator. This mechanism enables highly efficient long-distance heat transport with small temperature gradients. However, the attainable performance is limited by the capillary transport capability of the wick structure, which depends on transport length, orientation relative to gravity, and mechanical deformation of the heat pipe.

To establish a flight-representative thermal architecture, a dedicated experimental campaign was conducted to investigate the most relevant integration aspects. First, a fully metallic interface technology based on a multi-step soldering process was developed at Fraunhofer ILT. The process enables the integration of heat pipes into copper and metallized aluminum interface blocks while preserving thermal performance, mechanical robustness, and compatibility with laser-induced contamination requirements. In addition, the same process enables the realization of cascaded heat-pipe assemblies for transport distances that exceed the practical limits of individual devices.

A second focus was the influence of gravity during ground qualification. Experimental investigations demonstrated that CWHPs exhibit nearly identical thermal behavior across all relevant orientations as long as the operating point remains sufficiently below the capillary limit of the worst-case orientation. Figure 9 b) presents the thermal characterization results of a representative CWHP assembly in three different gravity orientations. Each measurement point corresponds to a steady-state operating point. The temperature difference ΔT increases approximately linearly with heat load until the capillary limit is reached and the dry out of the evaporator begins. While the capillary limit depends on the gravity vector, the thermal resistance in the nominal operating regime remains nearly unchanged. This confirms that CWHPs can provide reproducible and orientation-independent temperature control for the modified Aeolus-2 LTA EM, provided that sufficient margin to the worst-case capillary limit is maintained. The results therefore provide a clear design rule for achieving gravity-independent thermal performance during both terrestrial testing and microgravity operation.

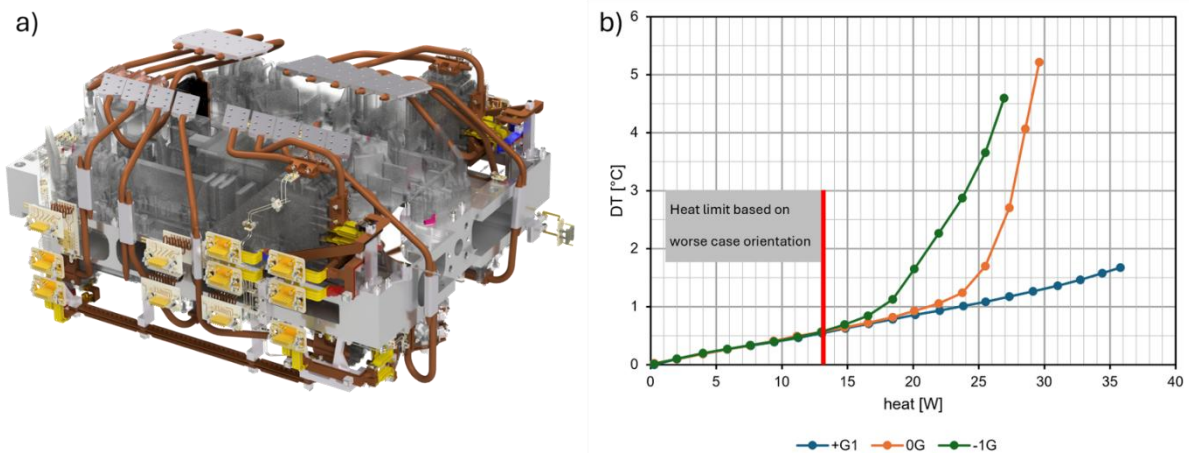


Figure 9. a) ALTA optical bench CAD model with highlighted TCS. b) Performance diagram of a heat pipe assembly in three orientations with respect to gravity.

The impact of routing geometry was analyzed using representative bent heat pipe configurations. Measurements showed that the thermal resistance remained essentially unchanged when minimum bending radii were respected. Only a minor reduction of the capillary limit was observed at high heat loads. These results confirm that complex three-dimensional routing of CWHPs can be realized without significantly affecting thermal performance.

Finally, the performance variation between nominally identical heat pipes was investigated. A dedicated pre-characterization methodology revealed noticeable differences in thermal conductance between individual devices. Rather than treating this variability as an uncertainty, it was incorporated into the thermal design process. Heat pipes with superior performance were assigned to high-power or long-distance interfaces, while less performant devices were allocated to thermally less demanding locations. This approach provides an additional degree of freedom for temperature matching without increasing system complexity.

The resulting heat-pipe-based thermal architecture provides a lightweight, fully passive, contamination-safe, and scalable solution for space lasers. The developed design, manufacturing, integration, and qualification methodology forms the basis for the thermal implementation of all fifteen interfaces and is directly applicable to future high-energy spaceborne laser systems with even higher thermal loads and more demanding integration constraints.

The final operating point of the pump laser is not yet known precisely, as the QLEO BB experiments have not yet been completed. The pulse energy that the pump laser must deliver depends on the conversion efficiency determined in those experiments. At present, we are assuming the absolute worst-case scenario, namely that the full pulse energy for which the Aeolus-2 LTA EM was designed is actually required at a PRF of 100 Hz. Accordingly, several CWHP units are being procured and tested for the components subject to the highest CWHP loads – essentially the amplifier pumps. The best of these will then be installed at the critical points.

6. CONCLUSION

In this article, we reported on the adaptation of our Aeolus-2 LTA EM to meet the QLEO requirements, enabling it to serve as the pump source for that mission. The EM was originally designed to generate high-energy UV pulses for the Aeolus-2 mission. It features an electro-optically Q-switched, single-frequency seeded oscillator followed by two INNOSLAB amplifiers and a frequency tripling unit, designed to achieve over 150 mJ at 355 nm with a repetition rate of 50 Hz. The optomechanical design employs a monolithic baseplate with isostatic mounting, precision-soldered optics, and a hermetically sealed, contamination-free housing. Thermal management is based on CWHPs that directly dissipate waste heat from pump diodes and laser crystals, ensuring minimal temperature gradients in the laser base plate and high stability.

The infrared section of the EM is ideally suited to serve as a pump source for a frequency conversion unit that converts the pump radiation from 1,064 nm to the QLEO wavelength of 935 nm. Such a frequency conversion unit is currently being developed at ILT and is being set up there as the QLEO BB. The QLEO BB is currently being tested, with the Aeolus-2 BB serving as the pump source, operating at a PRF of 100 Hz, which is the minimum PRF requirement for QLEO. Hence, to function as a pump for QLEO, the EM must also be operated at 100 Hz, which is twice the design PRF and would result in a doubling of the thermal load. As the TCS for the EM was not oversized, heat dissipation is the limiting factor for the EM's average power output. Depending on the conversion efficiency of the QLEO BB, the pulse energy of the EM may be reduced slightly, which would lower the thermal load accordingly.

By the time it was decided that the Aeolus-2 LTA EM would serve as the QLEO pump, the laser including the TCS had been fully designed, the oscillator had been integrated and tested at a PRF of 50 Hz, and the pumps for the first amplifier had been assembled. Following the decision, the oscillator was operated at 100 Hz without being readjusted and without any changes to the control parameters. Extensive characterization of the oscillator showed exceptional robustness. Pulse energy remained above 9.4 mJ at both 50 Hz and 100 Hz, with beam quality $M^2 < 1.25$ and stable pointing. The oscillator's performance was virtually unaffected by temperature variations of the crystal and the pump diodes in a range of 12 K. Frequency stability, spectral linewidth, and energy stability all met or exceeded requirements also at 100 Hz operation. The pumps for both amplifiers also operated flawlessly at 100 Hz, with linear power scaling and no degradation due to thermal effects. These results show that the optical design and packaging are suitable for 100 Hz operation.

The thermal management system was refined through a dedicated experimental campaign. A soldering-based interface technology enabled integration of heat pipes into metallic blocks which serve as heat sinks for the heat dissipating components, and tests showed that orientation relative to gravity had negligible influence on performance as long as sufficient margin to the capillary limit was maintained. Bent routing paths did not significantly degrade thermal resistance. Finally, a pre-characterization methodology allows the selection of the best-performing heat pipes for the most demanding interfaces. This passive, lightweight, and contamination-safe thermal architecture is directly applicable to future high-energy spaceborne lasers. Overall, the results confirm that the optical, optomechanical, and thermomechanical concepts

are fully suitable for space operations, and the laser can be adapted to serve as a reliable pump source for QLEO. Once the EM is fully integrated, it will be used to pump the QLEO breadboard, thereby validating the overall concept for a future QLEO mission.

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REFERENCES

- [1] Esser, D., Giesberts, M. et al., "Optomechanical design of a 150 mJ single frequency UV laser for the AEOLUS-2 mission," Proc. SPIE 12777, International Conference on Space Optics — ICSO 2022, 127770N (12 July 2023).
- [2] Esser, D., Giesberts, M. et al., "Laser transmitter engineering model for the Aeolus-2 mission," Proc. SPIE 13699, International Conference on Space Optics — ICSO 2024, 136991C (28 Jul 2025).
- [3] Russbüldt, P. et. al., "Innoslab Amplifiers," Selected Topics in Quantum Electronics, IEEE Journal of 21(1), 447–463 (2015).
- [4] Löhring, J., Winzen, M., Faidel, H., Miesner, J., Plum, D., Klein, J., Fitzau, O., Giesberts, M., Brandenburg, W., Seidel, A., Schwanen, N., Riesters, D., Hengesbach, S. and Hoffmann, H.-D., "Key optical components for spaceborne lasers," SPIE Proceedings, 97300O (2016).
- [5] Faidel, H., Gronloh, B., Winzen, M., Liermann, E., Esser, D., Morasch, V., Luttmann, J., Leers, M. and Hoffmann, D., "Passive alignment and soldering technique for optical components," SPIE Proceedings, 82351I (2012).
- [6] Strotkamp, M., Elsen, F., Löhring, J., Traub, M. and Hoffmann, D., "Two stage Innoslab amplifier for energy scaling from 100 to 500 mJ for future lidar applications," Appl Opt 56(10), 2886–2892 (2017).
- [7] Hahn, S., Bode, M., Luttmann, J. and Hoffmann, D., "FULAS: high energy laser source for future LIDAR applications," 194 (09.10.2018 - 12.10.2018).
- [8] Luttmann, J., Klein, J., Plum, H.-D., Hoffmann, H.-D., Hahn, S. and Bode, M., "FULAS: Design and test results of a novel laser platform for future LIDAR missions," SPIE Proceedings, 100821H (2017).
- [9] Löhring, J., Meissner, A., Hoffmann, D. et. al., "Diode-pumped single-frequency-Nd:YGG-MOPA for water–vapor DIAL measurements: design, setup and performance," Appl. Phys. B 102, 917–935 (2011).
- [10] Kallmeyer, F., Hermerschmidt, A., Eichler, H. J., Klingenberg, H. H., Nikolov, S., "Injection seeding of a high energy Ti:Sapphire laser for water vapor detection around 935 nm," in Advanced Solid-State Photonics (TOPS), C. Denman and I. Sorokina, eds., Vol. 98 of OSA Trends in Optics and Photonics (Optica Publishing Group, 2005), paper 718.
- [11] Elsen, F. et. al., "Demonstration of a 100-mJ OPO/OPA for future lidar applications and laser-induced damage threshold testing of optical components for MERLIN," Opt. Eng. 57(2) 021205 (23 September 2017).
- [12] Amediek, A. et. al., "CHARM-F-a new airborne integrated-path differential-absorption lidar for carbon dioxide and methane observations: measurement performance and quantification of strong point source emissions," Appl Opt 56(18), 5182–5197 (2017)
- [13] Livrozet, M. et. al., "Optical and optomechanical design of the MERLIN laser optical bench," Proc. SPIE 11852, International Conference on Space Optics — ICSO 2020, 118522Q (11 Jun 2021).
- [14] Livrozet, M. et. al., "QLEO – Frequency Converter at 935 nm for Water Vapor LiDAR," Proc. International Conference on Space Optics — ICSO 2026, to be published
- [15] Henderson, S. W., Yuen, E. H., Fry, E. S. "Fast resonance-detection technique for single-frequency operation of injection-seeded Nd:YAG lasers," Opt. Lett. 11, 715-717 (1986)