International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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Sven Hahn

Markus Bode

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Dieter Hoffmann

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111805F · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536114

FULAS: High energy laser source for future LIDAR applications

Sven Hahn[*a], Markus Bode[a], Jörg Luttmann[b], Dieter Hoffmann[b],
[a]Airbus Defence and Space GmbH, 81663 Munich, Germany, Email: sven.hahn@airbus.com;
[b]Fraunhofer Institute for Laser Technology, Steinbachstraße 15, 52074 Aachen, Germany

ABSTRACT

Reliable high energy laser sources had been proven in the past to be the bottle neck for space-borne LIDAR instruments. The presented FULAS laser optical design concept and the developed technologies define a technology baseline for a high variety of potential LIDAR applications. The technology provides a reliable space compatible system design, optimized with respect to lifetime and in especial laser induced contamination. The applied design principles and modularity allow proven energy scalability, flexible modes of operation and a manifold of opportunities for tailoring of the output wavelength. The concept, some details of the design and the potential for future application are addressed in this publication

Keywords: LASER, LIDAR

1. INTRODUCTION

For atmospheric LIDAR instruments in space, a manifold of scientific applications exists. But due to the lack of high energy laser sources providing the performance, reliability and lifetime necessary to operate such instruments in space, realization is currently seen as still critical in the community. In order to improve this situation ESA and DLR initiated a technology development project, named FULAS, for a space representative demonstrator of a versatile single frequency solid state laser in 2008.

The design is based on a seeded, actively q-switched, diode pumped Nd:YAG laser-oscillator and power amplifier configuration with external frequency tripling.

Further, the laser design - which has already been presented in detail at ICSO 2014 [1] - is realized with special attention on Laser Induced Contamination (LIC) issues, e.g. applying special glue free technologies for opto-mechanical mounting and avoiding any kind of organic materials.

The technical baseline for the specifications of FULAS is strongly linked to the original requirements of the ATLID mission at begin of the Phase B. In this specification, the system should provide single frequency laser pulses (<30 ns at 100 Hz) of about 30 mJ at 355 nm. With start of the Methane Remote Sensing Lidar Mission (MERLIN) [4],[5] (DLR/CNES, Phase C/D ongoing), the FULAS technology was selected as baseline for the laser design. As a consequence, the main objective of FULAS has been adapted to support the MERLIN development. The implementation of the foreseen UV-conversion stage was postponed and development efforts focused on the oscillator and power amplifier section, to provide early performance results for the 1064 nm part. This part is conceptually similar for MERLIN and FULAS.

The full optical performance in the IR has successfully been demonstrated in 2016, as already presented in detail at ICSO 2016 [3]. After integration of the laser optical bench into its hermetically sealed and pressurized housing, the project performed the thermal vacuum test campaign, consisting of non-operational thermal cycling and full performance demonstration for the operational temperature range. During this campaign an absolute stable operation, fully compliant to the specifications, was demonstrated. Following the TV campaign an endurance test of 10 weeks of duration was performed in Summer 2017, without any detected degradation of the laser.

The results of the work spent on FULAS in the past years have demonstrated successfully the possibility to transfer the performance of state of the art laser technologies, as used in COTS system, into a space-compatible design.

Thanks to its proven scalability and customizability, the design concept is also suitable as a baseline for manifold of potential future LIDAR missions.

One realized example currently is the use in the already mentioned French-German Climate Mission MERLIN, utilizing a downscaled version of the FULAS Oscillator and Amplifier to pump an OPO, which is built by applying the FULAS technologies and baseline designs. The presentation will focus on the demonstration of the technology and design versatility and its ability to adapt FULAS to manifold future LIDAR missions. An overview of the already demonstrated performance capabilities will be provided.

2. OVERAL SYSTEM DESIGN

2.1 Major design requirements

Typical space instrument requirements account for the very limited power, mass budgets, high vibrational loads and large thermal ranges. Further high stiffness and extraordinary geometrical stability for optical instruments are driving the design of FULAS as well as the laser application specific critical requirements, detailed below.

One of the most critical design aspects to operate a high energy laser in space is the risk of degradation of optical coatings due to high energy laser radiation. The lessons learned from former programs have focused the attention on effects by Laser-Induced-Contamination (LIC). Hence for optical components exposed to high energy laser radiation, extraordinary cleanliness even on molecular level is mandatory. This is in particular valid for instruments in the UV spectral range, such as FULAS. Therefore the avoidance of outgassing organic substances like glues and plastics, even in variants labeled as "low outgassing", is a major design requirement.

One well-known measure to mitigate the LIC criticality is the presence of an Oxygen containing atmosphere, which demands a hermetically sealed and pressurized housing for operation in space. Furthermore, a pressurized environment also is beneficial for the damage threshold of some optical coatings, thus increasing the reliability and durability of the system. Consequently, a pressurization requirement for the whole laser housing, including necessary feedthroughs and the exit window, has been established. Starting from 1 bar initial pressure, a pressure drop in space/vacuum of not more than 0.1 bar over lifetime (3 years) is specified to guarantee stable conditions.

Further design driver is the need for efficient extraction of the thermal loads, independent from the mechanical I/F, and active stabilization of the temperature of the main heat sources (laser diodes), while limiting the overall thermal gradients and resulting thermoelastic deformations.

2.2 System overview

The FULAS laser is built as a pressurized and hermetically sealed housing of about 500 x 200 x 300 mm³, with an isostatic mounting I/F for accommodation e.g. into an LIDAR instrument structure. As shown in Figure 1, the central frame of the housing provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for the miniature loop heat pipes (LHP) and a beam exit window. Furthermore two connectors for purging and pressurizing the housing before final sealing are implemented.

An external cold plate attached to the central frame of the housing serves as condenser for the LHPs and as overall system thermal I/F.

The mounting of the laser optical bench is optimized for mechanical decoupling from the surrounding structure. By isostatic mounting inside the housing central frame, the optical bench is insulated from stress induced by the instrument environment. Particularly, the design features a maximum tolerance with respect to mechanical deformation due to environmental pressure changes.

The compliance of the basic optical concept to the requirements, using conventional mounting technology and components, had been validated before in air-borne LIDAR applications, operated by DLR. To achieve space compatibility, the design is optimized with special attention on LIC issues introducing several new technologies.

To reduce LIC effects, the hermetically sealed housing provides lifetime atmospheric pressure conditions for the laser optical system. Use of innovative soldering techniques for optics alignment and glue free mounting, concepts for the electrical harness avoiding plastic insulation, a newly developed friction stir welding (FSW) process for the pressurized housing and other details enable the realization of the design goal of an "all metallic, ceramic or glass design" by very few exceptions only.

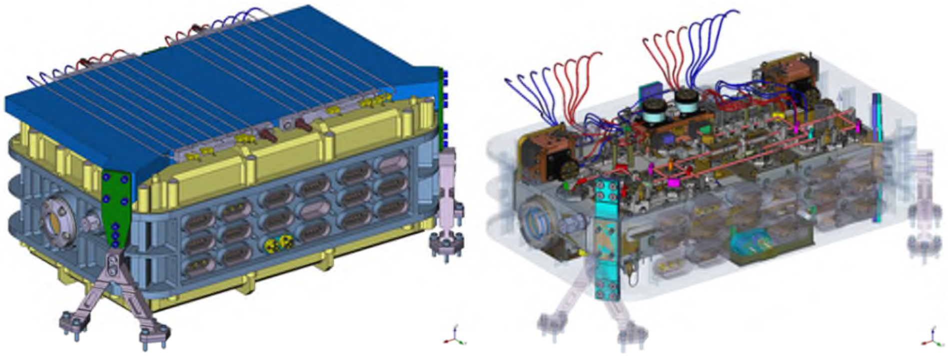


Figure 1: FULAS pressurized housing with top-mounted cold plate (left) and internal optical bench (right)

2.3 "Clean" Pressurized housing

Due to the need of a lightweight design while providing the thermal conductivity to support thermal balancing, Aluminium is the material of choice for the housing. To provide access to both sides of the double sided optical bench, a symmetrical open frame is used, carrying the isostatically mounted optical bench (Figure 1). The frame is closed by two symmetric bolted covers, primary-sealed by special metallic gaskets, enabling easy reopening and resealing during assembly and testing. For final life-time sealing, the covers are designed to be welded, providing a reliable redundant secondary sealing.

The challenging part of the design is the need of a multitude of various feedthroughs (electrical, thermal and fibre-optical) to operate such a system, as well as a high quality optical beam exit window. To fulfil the cleanliness and lifetime requirements, only thermal joining methods as welding, brazing or glass/ceramic potting are applicable. For brittle materials like glass a CTE-matched joint is necessary, which typically leads to low CTE metals like Steel or Titanium, not compatible with an Aluminium housing and conventional joining technology. The special modular design realized for FULAS is based on different feedthrough modules in similar geometry and with Titanium or Stainless Steel body. To overcome the incompatibility of conventional welding methods to join this materials with an aluminium housing, a special joining process is applied. A mechanical Friction Stir Welding (FSW) process was optimized in the frame of the project, using a special welding effector developed by Airbus Group.

2.4 Active thermal management

To allow an efficient rejection of about 100 W of thermal load inside the pressurized housing and minimize thermal gradients across the optical bench, mini Loop Heat Pipes (LHP) are directly attached to the major heat sources inside the laser housing, as illustrated in Figure 2.

Four pairs, each operated in one-out-of-two cold-redundancy configuration, are connected with their evaporators directly to the main heat sources on the optical bench, enabling selective cooling directly at the source. By its semi-rigid tubing combined with dedicated housing feedthroughs the heat is efficiently transported out of the housing towards the external cold plate. Due to the low mechanical stiffness of the tubes, the optical alignment and the mechanical decoupling of the optical bench is conserved and not affected by the thermal I/F.

A very important feature of the LHP technology contrary to classical heat pipes, is the possibility of efficient control of the conductivity by active derating using an attached inhibition heater. By constant powering the heater of one LHP out of the redundant pair with typically a maximum of 1.5 W, the inhibition is suitable to completely disable the relevant LHP and therewith realize the cold-redundancy design.

For the presented System, the necessary precise and efficient temperature control is realized by applying less than 0.5 W of control power to the respective LHP evaporator. Reliable suppression of the redundant LHP is achieved applying constantly 0.7 W to each redundant LHP evaporator.

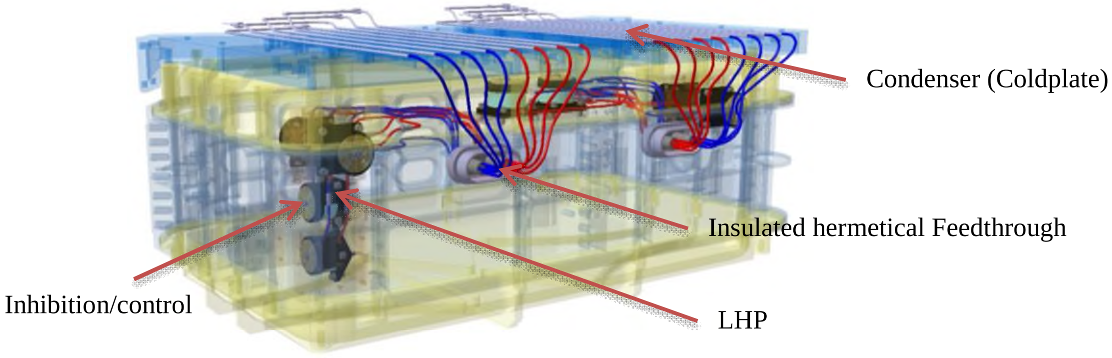


Figure 2: Housing with LHP – Thermal management Sub-System

3. LASER OPTICAL DESIGN

3.1 Operation principle

The FULAS system as presented is a high power laser system using solid state laser technology which is state of the art for industrial applications. The laser optical design consists of a frequency stabilized Nd:YAG Master Oscillator – Power Amplifier (MOPA) configuration with external frequency tripling by non-linear third harmonic generation (THG). The main laser parameters for IR and UV are listed in Table 1, including also the values already demonstrated in the IR during the past test campaign.

The master oscillator includes a Nd:YAG crystal rod as gain medium, end-pumped from both sides by fiber coupled laser diode modules. For pulsed operation, the resonator is q-switched by use of a pockels cell. To achieve single longitudinal mode operation and to fulfill the stringent requirements on the pulse quality, the oscillator is injection seeded and cavity controlled by a piezo driven end mirror. The reference laser source for seeding is placed outside of the housing and transmitted via polarization maintaining optical fiber and dedicated hermetical housing feedthrough.

For the amplifier, the InnoSlab concept, developed by the Fraunhofer Institute for Laser Technology (ILT), is applied. This concept is ideal for high energy and high efficiency single mode power amplifiers [6]. The Nd:YAG slab crystal is end pumped from both sides by use of high power diode stacks and appropriate beam shaping optics as shown schematically in Figure 3 The signal beam is folded 7 times through the amplifier crystal in a single pass configuration. By choosing appropriate mirror radii and signal beam divergence the beam is widened with every pass to keep the fluence constant. Hence the fluence can be kept high enough for efficient amplification while remaining away from the damage threshold. With an input signal of about 9 mJ, the presented FULAS amplifier is designed to generate output pulse energy of up to 90 mJ at 1064 nm, demonstrated during the past test campaign.

Table 1: Laser major parameter specifications (IR, UV) and Measurements (IR)

Parameter	**IR**		**UV**	
	Specification	**Measured**	**Specification**	**Target**
Wavelength	1064 ± 1 nm		355 ± 1 nm	
Puls Repetition Frequency	100 Hz			
Energy per pulse	> 85 mJ	90 mJ	> 27 mJ	36 mJ
Energy short term stability (p. to p. over 1.4 sec)	< ± 3 %	< ± 2 %	< ± 10 %	< ± 5 %
Optical-optical Efficiency	> 20 %	19.2 % (*)	> 7 %	> 9 %
Pulse duration	< 50 ns	26 ns	< 50 ns	

Parameter	**IR**		**UV**	
	Specification	**Measured**	**Specification**	**Target**
Spatial Mode / Beam quality	Gaussian / M^2 < 2	Gaussian / M^2 1.54	Gaussian / M^2 < 2	
Longitudinal Mode	Single	Single	Single	
Pulse linewidth	--	19.6 MHz	< 50 MHz	
Frequency stability over1.4 s	< 1.33 MHz rms	< 1 MHz over 10 s	< 4 MHz rms	< 1 MHz rms
Boresight stability – short term (p. to p. over 1.4 sec)	< ±75 µrad	< ± 20 µrad (p-p over 10 min)	< ±75 µrad	
Boresight stability – long term (p. to p. at T = 21±2 °C)	< ± 150 µrad.	< ± 50 µrad (**)	< ±150 µrad	
(*) Reduced efficiency mainly due to non-optimal selection of Pump diodes. (**) Measured over 5 days operation during thermal vacuum cycling within the operational Temperature range				

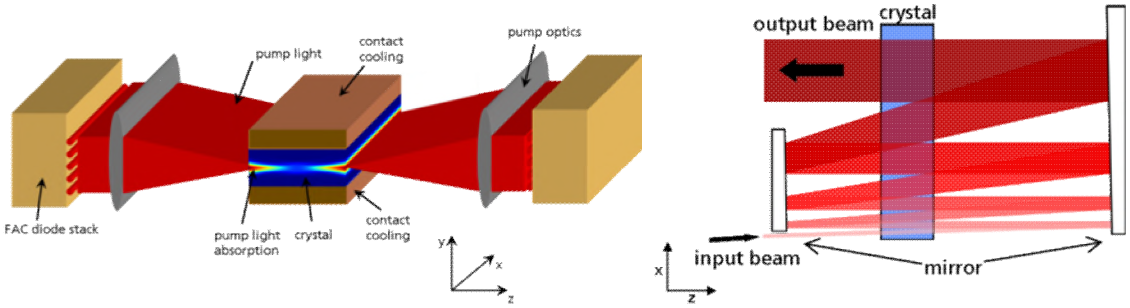


Figure 3. Schematic of InnoSlab Pump configuration (left) and folded signal beam path (right)

After the amplifier, the IR beam caustic is adjusted to fit to the optimum beam diameter for the frequency conversion. To triple the laser frequency, two LBO crystals are used in critical phase-matching configuration. The first one with type I process (oo→e) for second harmonic generation (green, 532 nm) and the second one with type II process (oe→o) for third harmonic generation (UV, 355 nm). In favour for high life time of the frequency conversion stage, the fluence on its optical surfaces is designed to rather low levels. With the resulting very conservative conversion efficiency of at least 30% [[9],[10]], which has been verified in many operational laser system, the requested output pulse energy of about 27 mJ at 355 nm wavelength is generated.

3.2 Optomechanical design

The laser optical bench is mounted inside the pressurized housing central frame by use of three isostatic mounts. The laser is assembled on both sides of the bench, as shown in Figure 4. The lower side carries the oscillator, while the power amplifier and the frequency conversion are situated on the upper side.

To realize an efficient and compact laser system meeting the stringent mechanical and cleanliness requirements for a reliable and stable space-borne operation, new mounting technologies are introduced. These technologies have been developed at Fraunhofer ILT in the frame of a DLR funded research project. Compact, precise, stable and glue free mounting of all optical laser components is realized by use of a soldering technology. Temperature cycling tests of soldered mirrors demonstrated stability of better than 10 µrad, as required for adjustment sensitive components like resonator mirror mounts. A reflow soldering process is applied to less sensitive components like pump optics, where the position accuracy is driven by the mechanical tolerances. For components requiring high alignment accuracy, an innovative active alignment technique is used. The so called "Pick & Align" process enables active high precision 6-axis alignment of the optics during soldering. Adjustment by repeated melting of the solder is possible multiple times, thus enabling the alignment of the laser oscillator end mirrors directly on the optical bench, without need for additional mechanical alignment capabilities.

Further examples of the efforts to avoid contaminating materials are the two high energy optical isolators implemented to avoid feedback from the oscillator into the seed fiber and from the amplifier into the oscillator. Typically the necessary permanent magnets are assembled by gluing. For FULAS a newly developed, glue free isolator design is introduced.

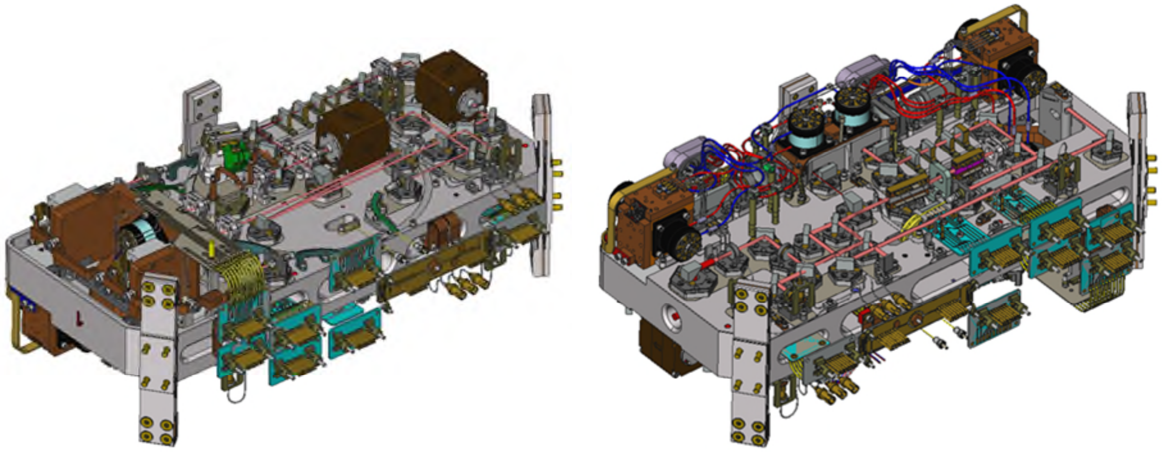


Figure 4: Two sided optical bench, showing Oscillator side (left) and Amplifier/THG side (right).

3.3 "Clean" internal Harness and Electrical Design

For operation of FULAS more than 90 different electrical connections are necessary, covering low power control and monitoring signals, coaxial cabling as well as high current power supply (>100 A). One major contributor for the mentioned critical LIC issue is the pollution due to outgassing of organic and plastic materials as used for electrical insulation. Hence an electrical design is realized, avoiding any kind of plastic insulation. The main harness for distribution of the signals at the optical bench is realized by ceramic printed circuit boards manufactured in thick film technique. For high current power supply of the pump diodes, copper current bars are used, also to minimize electrical losses. To reduce the amount of electrical wiring nearby the optical components, parts of the main harness are embedded in tunnels machined through the centre of the optical bench. For connecting the individual electrical components, bare wires are used, fixed by insulating ceramic brackets. All connector assemblies utilize ceramic or glass for insulation, which is also valid for the sealing of the electrical housing feedthroughs.

To avoid the need of high voltage signals guided over long path and through the housing wall, the driving electronics for the pockels cell, operating at 4.6 kV with about 10 ns rise/fall time, is placed close to the cell inside the housing. For contamination reasons, the tailored electronic is built-up inside a separate hermetically sealed box, visible on the photograph in Figure 6.

4. ASSEMBLY AND TEST CAMPAIGN

4.1 Assembly and Integration

The FULAS design including all subassemblies and developed processes were realized and verified within two years. After individual subassembly tests (including e.g. environmental testing (vibrational and thermal vacuum) of a representative structural model of the housing), the complete housing was successfully manufactured, assembled (see Figure 5) and tested. Extensive testing was performed with the integrated LHP thermal subsystem. The performance and active thermal control capability of the LHP system was operationally verified before integration of the sensitive optical system. In parallel, the optomechanical assembly had been performed. After successful test of the individual components and subassemblies, the optical bench had been equipped and the oscillator as well as the amplifier were aligned.

After wedding of the aligned optical bench with the housing frame and the LHP thermal management system, the housing was closed (Figure 6) and the IR performance of the laser system was successfully demonstrated (see Table 1 for results).

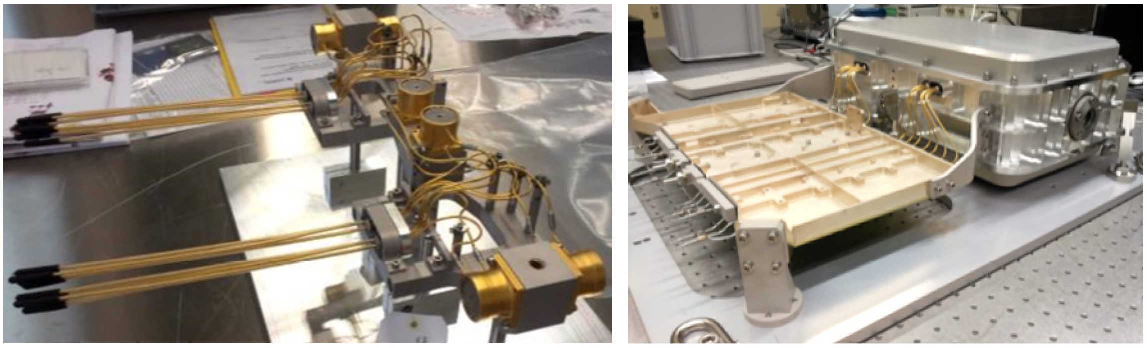


Figure 5: *Left*: LHP-Thermal subsystem ready for integration into the housing frame. *Right:* Pre-assembled pressurized housing, ready for thermal sub-system testing and integration of the laser optical bench.

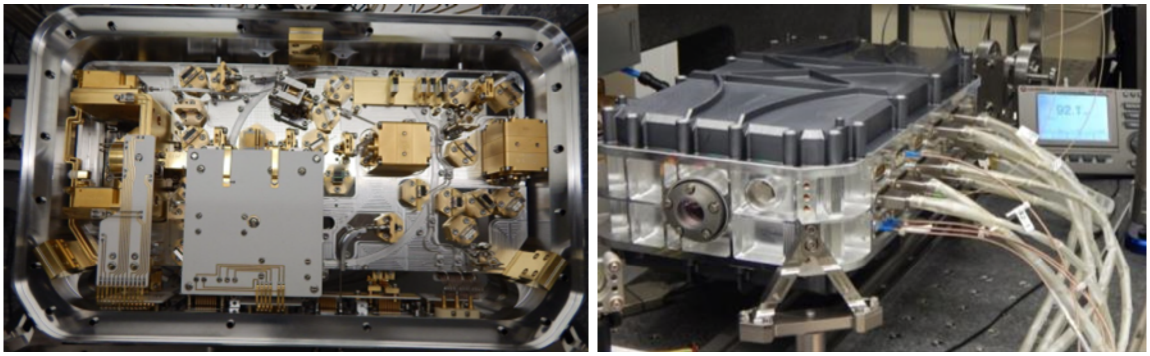


Figure 6: Oscillator side, including Pockels-Cell HV-switch of the optical bench after integration into the pressurized housings central frame (left) and closed laser with housing during first performance test.

4.2 Thermal Vacuum Test campaign

In Summer 2016, the FULAS laser system was tested under thermal vacuum conditions (see Figure 7). In the frame of this test campaign, the temperature and pressure related performance parameters could be verified.

The insensitivity of the optomechanical design to external pressure changes was proven by laser operation and performance monitoring of the pressurized laser during test chamber evacuation and by comparison of the performance measured in laboratory environment and under vacuum. Therefore the major performance parameters (Pulse energy, beam profile, puls width and beam pointing) had been measured and recorded whenever the laser was operational. Also the housing internal pressure was monitored during the vacuum test campaign, demonstrating the capabilities of the (primary) hermetical sealing concept to withstand the applicable non-operational temperature range of -30 °C to +50 °C.

Figure 7: *Left:* Laser in preparation for thermal vacuum testing; *Right:* test facility with integrated laser and external test setup for online laser performance measurement

During the second part of the test campaign, the laser was cycled within its specified non-operational temperature limits. In between the individual cycles, the system was thermalized at ambient level and operated for comparison of performance related laser parameters, demonstrating all measured performance parameters stable within the specified requirements.

As proven for the overall optomechanical system stability, one of the most important test results is the demonstration of the required pointing stability of the laser beam. By use of a customized Autocollimator Setup with in-house data acquisition and evaluation software and a mirror mounted on an isostatic frame close to the beam exit window of the housing, the pointing stability of the beam was verified directly by measurement with respect to the laser mechanical I/F.

4.3 Endurance Test Campaign

In summer 2017 the laser system was operated under stable environmental conditions for a periode of more than 8 weeks, to verify the stability of its performance. Therefore the pulse energy, beam diameter and pointing had been recorded continuously. Furthermore the impact of instabilities in the active controlled LHP thermal control system had been tested.

Again, all performance parameters are verified successfully within specification and no performance relevant damage or degradation had been observed.

5. SYSTEM VERSATILITY

The potential and capabilities of the laser optical design (see Figure 9) has been proven in the past in several projects, ranging from laboratory bread boards up to operational air-borne LIDAR applications: Stable single frequency operation in single and double pulse mode at variable repetition rate in continuous or burst mode, a demonstrated pulse energy range from single mJ up to 500 mJ in the NIR, capable for high efficiency frequency conversion to the green or UV by frequency doubling/tripling as well as conversion within NIR spectral range by use of an OPO. The A2D2G air-borne Doppler LIDAR instrument currently in final preparation will provide more than 60 mJ at 355 nm. It's based on the same optical design as FULAS, but with standard optomechanical and thermal design approach.

Further demonstration of the versatility and energy scalability of the FULAS platform is in progress. Most important examples are shown in the subsequent sections

5.1 MERLIN – Methane Remote Sensing Lidar Mission

MERLIN is a French-German climate mission. The French (CNES) satellite platform carries a German (DLR) LIDAR DIAL instrument for Methane observation in the earth atmosphere.

The instrument will use a modified version of FULAS. A downscaled IR-section of the seeded Nd:YAG MOPA, operated in 20 Hz double pulse mode, provides about 30 mJ at 1064 nm for pumping an integrated OPO. The seeded OPO will provide the double pulses as necessary for DIAL with 9.5 mJ and two alternating wavelengths at about 1640 nm.

The project is currently in Phase C/D, which had been initiated in 2016. The laser optical design is already demonstrated on breadboard level and the procurement and manufacturing of the major part of the components is ongoing, heading for qualification testing of the Laser EQM in 2021 and availability of the flight model one year later.

Figure 8: Preliminary Design of the MERLIN laser source

5.2 Wind LIDAR (Aeolus next generation)

The FULAS optical architecture is easily scalable in its output power by adapting the slab crystal width and number of folds or by sequential operation of multiple amplifier stages. Both variants are already demonstrated with more conventional laser designs, e.g. in the 2nd generation of the ALADIN Air-borne Demonstrator (A2D2G), built for DLR, and the two CharmF systems [[5],[8]] operational at DLR since end 2013, providing up to twice the FULAS IR pulse energy. Another up scaled version of the laser design had been built as laboratory bread board, demonstrating more than 500 mJ at 1064 nm by using two sequential amplifier stages [7]. With this, a 200 mJ output pulse energy at 355 nm is considered as feasible relying fully on demonstrated technologies with maturity of TRL3 or above.

Combined with the high acceptance of the Amplifier with respect to higher repetition rates (e.g 100 - 200 Hz), this leads to an possible increase of the average output power by at least a factor of 5, compared to the current ALADIN laser design on AEOLUS, with at least a factor of two better efficiency.

Also alternative approaches of lower pulse energy (< 10 mJ) at high repetition rates in the kHz range are feasible and demonstrated with conventional systems [6] based on the same technology.

5.3 CO_2 IPDA and Water Vapour

By integrating the OPO technology as demonstrated in MERLIN, also suitable sources for CO_2 IPDA (about 2050 nm or 1570 nm, ≥ 50 Hz, > 30 mJ double pulse or aletranatively single mJ with kHz repetition frequency) are feasible based on TRL3 or above designs. The same is valid for e.g. sources for water vapour detection, providing about 935 nm at ≥ 100 Hz and at least 150 mJ pulse energy as already demonstrated on the airborn CHARM-F system [8].

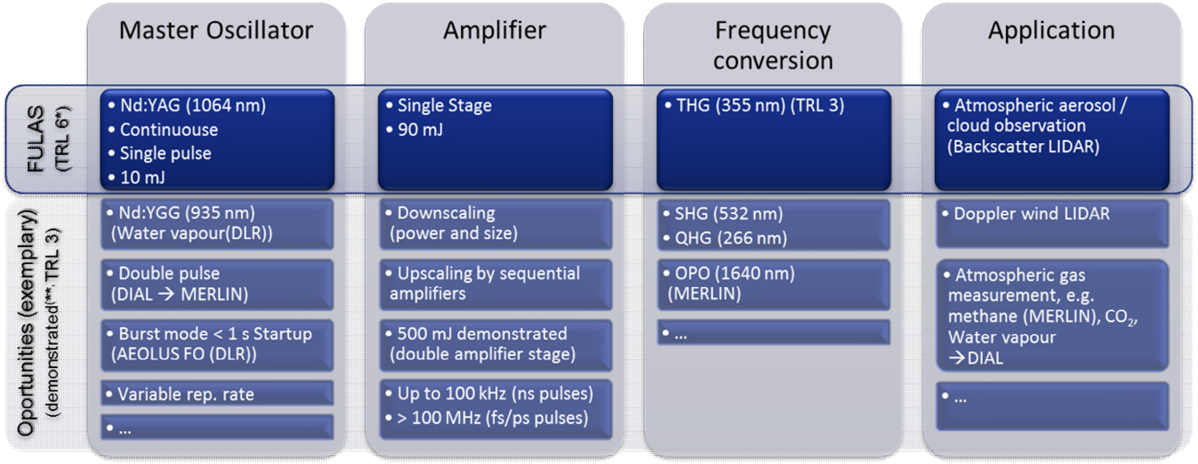
For such laser sources, all major TxA requirements can be completely covered by direct use of the FULAS and MERLIN technologies.

6. CONCLUSION AND OUTLOOK

The developed FULAS laser system provides a flexible, highly efficient laser technology platform, fundamental for a multitude of future space-borne LIDAR missions. The most important asset of this technology is the scalability and versatility of the laser optical concept, which is realized by the modular design approach. In combination with the newly developed pressurized housing technology and the "clean design", nearly free of organic materials, the high potential of FULAS as enabling technology for powerful Earth observation and scientific applications is obvious.

The operational verification of the FULAS design is demonstrated successfully under representative thermal and pressure conditions. After first h/w realization using the developed technology and designs, starting with setup and alignment of the FULAS master oscillator in 2014, the system was operated many hours during alignment and verification testing. Demonstrating full performance since first power on, Integration of the optical bench into the pressurized housing, road transport, operational vacuum testing and endurance testing had been performed, until now with full performance and without any need for readjustments. Even without full qualification status, this demonstrates the high reliability and robustness of the overall system design and setup.

In the near future, the FULAS laser demonstrator is foreseen to be modified by implementing the frequency tripling section and to demonstrate the performance in its intended UV-configuration. In nominal operation mode, the system will provide single frequency laser pulses of about 30 mJ pulse energy at a wavelength of 355 nm. Delivered with 100 Hz repetition rate and pulse duration in the range of 20 ns to 50 ns, this is suitable for e.g. atmospheric cloud and aerosol observation. To show the versatility and flexibility of the laser design concept, so called "advanced operation modes" might be verified also. One of these is the verification of high frequency doubling efficiency to make the system suitable e.g. as 532 nm pump source for an OPO for Water Vapour LIDAR application. Another option is the stable and efficient (without preheating) burst mode operation, preferred for e.g. some wind LIDAR applications.



	Master Oscillator	Amplifier	Frequency conversion	Application
FULAS (TRL 6*)	• Nd:YAG (1064 nm) • Continuouse • Single pulse • 10 mJ	• Single Stage • 90 mJ	• THG (355 nm) (TRL 3)	• Atmospheric aerosol / cloud observation (Backscatter LIDAR)
Oportunities (exemplary) (demonstrated(**, TRL 3)	• Nd:YGG (935 nm) (Water vapour(DLR)) • Double pulse (DIAL → MERLIN) • Burst mode < 1 s Startup (AEOLUS FO (DLR)) • Variable rep. rate • ...	• Downscaling (power and size) • Upscaling by sequential amplifiers • 500 mJ demonstrated (double amplifier stage) • Up to 100 kHz (ns pulses) • > 100 MHz (fs/ps pulses)	• SHG (532 nm) • QHG (266 nm) • OPO (1640 nm) (MERLIN) • ...	• Doppler wind LIDAR • Atmospheric gas measurement, e.g. methane (MERLIN), CO_2, Water vapour →DIAL • ...

*) Except Vibrational testing, performed on subassembly level only

**) For reference see e.g.: P. Russbueldt et al., "Innoslab Amplifiers", IEEE Journal of Selected Topics in Quantum Electronics (Volume: 21, Issue: 1, Jan.-Feb. 2015)

Figure 9: Versatility and scalability of the FULAS technology

7. ACKNOWLEDGEMENT

The FULAS project, performed under ESA contract No. Coo8/09/FF to 18256/04/NL/FF, is made possible by several assisting research and development activities. The used optics soldering technique was developed in the frame of the Optomech project under DLR contract No. FKZ-50EE904. The pre-developments for the pressurized Housing technology as well as the LHP implementation are supported by the MERLIN project under DLR contract FKZ-50EP1001 and intra-company R&D support.

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