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System concept and thermo-mechanical design aspects of a robust and efficient Laser Transmitter for the AEOLUS-2 mission

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ABSTRACT

Airbus Defense and Space GmbH, in cooperation with Fraunhofer ILT, is currently developing an engineering model (EM) of the laser transmitter for the AEOLUS-2 mission in frame of the ESA contract ALTA. . For this follow-up mission, a more powerful Laser transmitter is required, to provide single frequency laser pulses of 150 mJ energy.
The design focuses on maximizing the use of the heritage from previous space-borne laser designs of the projects FULAS (ESA, EM-like Technology Demonstrator) and MERLIN (DLR/CNES, French-German Climate Mission).
The FULAS laser comprises INNOSLAB based MOPA delivering IR laser pulses in the 100 mJ class at 100 Hz PRF. It has undergone a test program demonstrating outstanding thermal insensitivity and robustness and optical and mechanical stability, showing no degradation or misalignment at all after seven years.
The laser transmitter of MERLIN, evolved from FULAS, comprises a scaled MOPA, combined with a subsequent Optical Parametric Oscillator (OPO) for frequency conversion.
While the Laser opto-mechanical assembly (LASO) is developed by Fraunhofer ILT, Airbus Defence and Space GmbH is in charge of the system concept and the hermetically sealed Laser Housing (LASH) as well as the innovative thermal control system.
This publication will provide insight in the transfer of the FULAS and MERLIN system concepts to the Doppler Wind LIDAR Transmitter. Emphasis will be on the robust thermo-mechanical design, with its thermally and mechanically decoupled optical bench and the sophisticated thermal control system based on heat pipes for effective heat removal directly from the individual heat sources of the system. This design is chosen to provide hands off operation of the Transmitter over life time.

Keywords: LASER, LIDAR, MOPA, AEOLUS, Wind, CuH20 heatpipes

1. INTRODUCTION

Beside the already known criticalities arising from the operation of a laser in space, the AEOLUS2 mission has new additional key design drivers, namely

- Pulse energy increased by a factor of two compared to the AEOLUS, with increased efficiency in terms of laser power consumption and thermal loads
- Lifetime requirements extended from 3 years up to 5 years with a goal of 7 years.

<u>Increased output energy of laser can be achieved by:</u>

- Adding additional amplification elements
  → will increase complexity, mass and size
- Operating at higher efficiency set points (e.g. increased fluence, higher pump diode current, …) by reducing the safety and derating factors
  → will have a negative impact on component lifetime and/or will reduce the laser reliability numbers
- Accepting a reduced beam quality
  → Leads to a larger divergence of the beam with impact on the apertures of the instrument

<u>Increase of laser operational lifetime can be reached by:</u>

- Reduction of lifetime critical fluence to increase the reliability values of optical surfaces
  → will lead to a lower laser efficiency and therefore requires a higher power consumption
- Higher derating of the pump diode operational set points (current vs pulse duration)
  → will lead to a lower laser efficiency and therefore for a higher power consumption
- Decrease of laser diode operational temperature
  → will lead to a reduction of the maximum accepted thermal load due to negative impact on the cooling performance of the payload radiator

The general mismatch of such contradictory requirements for a laser is not new and has driven all laser design activities in the last decade and requires that some compromises must be made. A design approach that addresses the listed requirements while balancing the outlined negative impacts has been implemented in the FULAS technology demonstrator and more recently in the MERLIN flight module. The next paragraphs provide further insight into this design, paying special attention to the design of the laser housing and the thermal management system. This thermo-mechanical system is essential for minimizing any misalignment under varying thermal and mechanical load cases and for keeping the operational point of the optical system close to the optimum over full lifetime.

2. SYSTEM OVERVIEW

2.1 Overall Laser Concept

The Laser head (LAS), is comprised of the opto-mechanical assembly (LASO) isostatic mounted in the housing (LASH). This secures optical bench stability similar to an interferometric setup. Securing low distortion by mechanical forces of the LASO bench is one key concept to guarantee long term stability of the alignment.
The LASH is hermetically sealed and provides a stable pressurized environment for the LASO.
The pressure difference between the laser inner compartment and the space environment will lead to high mechanical forces with non-negligible deformations on LASH (ballooning effect). Due to the mechanical decoupling of the optical bench, the impact of the ballooning effect on the laser alignment is effectively eliminated. This guarantees stability of the laser alignment from ground to orbit and also during lifetime, even in the presence of delta pressure variations due to potential sealing imperfections.
The second source of alignment critical effects on the laser plate is the thermos-elastic deformation by thermal gradients of the bench by the high thermal loads at the active laser elements.

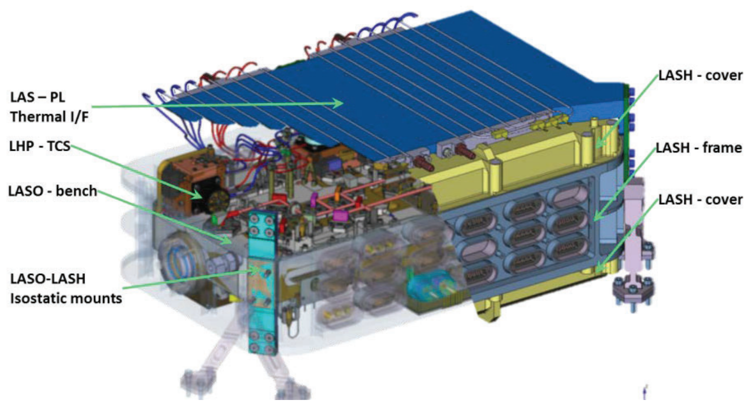

Figure 2-1: Laser concept - Key elements shown at the FULAS demonstrator

To minimize these deformations, the thermal interface is decoupled from the mechanical alignment critical structures. This is realized by laser internal heat pipes that provide the thermal hardware to reject effectively the power generated at the active elements of the LASO. The use of a heat-pipe based thermal control system (TCS) allows a highly efficient transport from the source at LASO level to the LAS – Payload Interface.
Finally the LAS mounting I/F to the payload is optimized to minimize stress in both directions and to secure a sufficiently high first Eigen frequency.

2.2 Details on key performance elements

Opto-mechanical mounting

In addition to the overall laser configuration concept, the laser design has also been optimized to reduce the amount of organic materials inside the laser by orders of magnitude. This will secure that the critical issue of the laser induced contamination (LIC) problem seen in AEOLUS and leading to a reduction of the mission lifetime is strongly mitigated.
This is realized by establishing a specific mounting technology relying on optical mounts with solder interfaces (C-mount) only, instead of gluing the optics [3]; [4]. This technology also delivers outstanding mount stability of few µrad tilt under thermally-induced stress over non-operational cycling and an extended operational temperature range, required for the not actively controlled MERLIN laser, of up to ±10 K.
Figure 2-3 shows an example of the achieved performance of this new mounting technology.

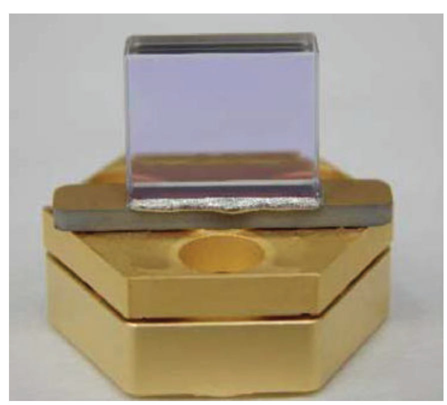

Figure 2-2: C-Mounts as used at LASO level

The graph shows the demonstrated angular stability for a C-mount over a non-operational range of -30°C to +50°C (left of the blue line) and the final accuracy after the settling effects induced by the cycling over an operational range of 20°C ±10°C (right of the blue line). As can be read from the lower half of the plot, the maximum deviation from the initial an alignment is less than 3µrad relative to the initial values.

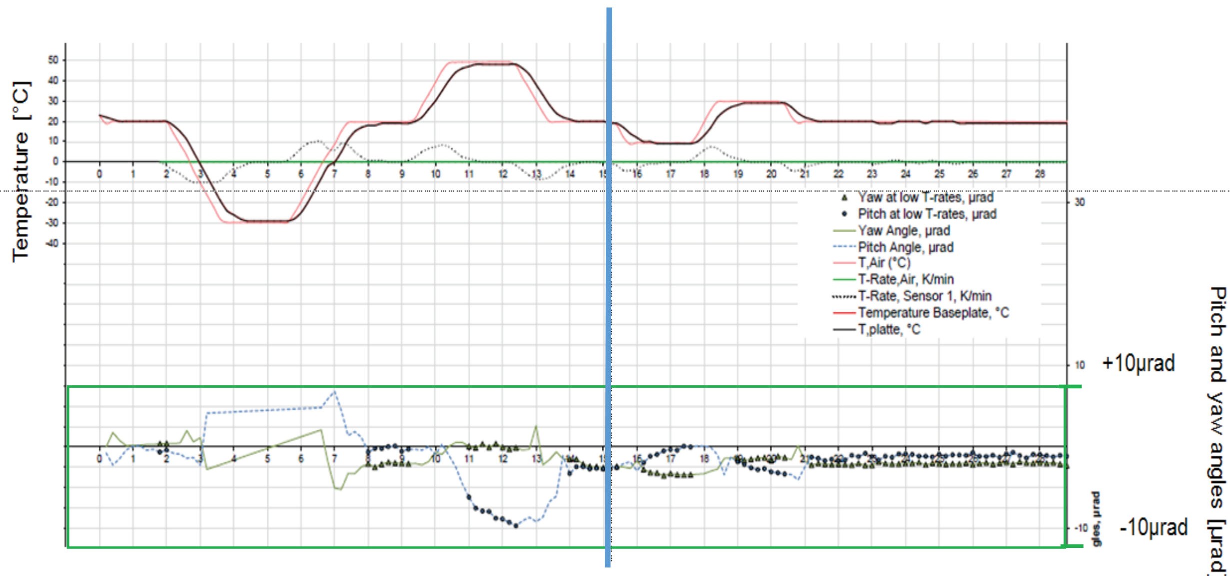

Figure 2-3: Demonstrated angular stability of a soldered opto-mechanical mount

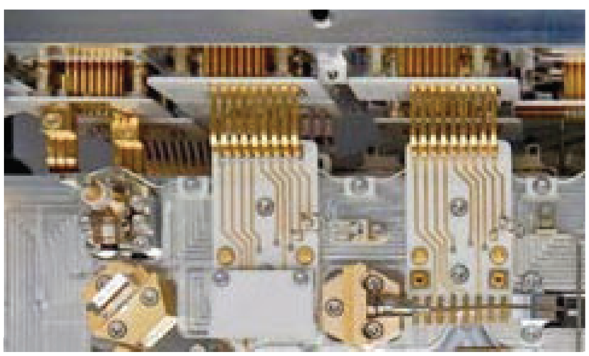

Figure 2-4: Organic free electrical Harness

Also the electrical harness, usually a major contributor for outgassing organic material, is built as a pure inorganic design. Skipping any flexible wiring with plastics insulation imposes significant challenges on the harness design, since all its components have to be either CTE-matched or CTE-compensated. FULAS and MERLIN (further described in [1]) have successfully implemented this concept using a combination of ceramic printed circuit boards and bare metallic conductors.

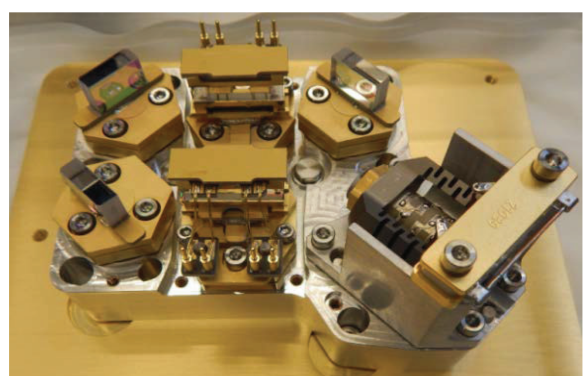

Figure 2-5: MERLIN OPO EQM cavity

In these two programs a full space qualification of the mounting technology and a representative performance demonstration of the complete system were performed. The qualification in FULAS covered thermal vacuum testing to space-relevant levels for the complete laser assembly. In Merlin, a component level and subsystem-level qualification of the most sensitive element the cavity controlled OPO ring cavity was done. The qualification has covered all thermal and mechanical qualification loads, including shock.

➔ No change of the alignment could be detected.

During the FULAS program, the developed technology demonstrator was stressed and tested under thermal loads in ambient and vacuum environment. The goal was to show the performance sensitivity to stress induced by non-operational thermal cycling, and to variation of the operational thermal environment. In addition the impact of long term operation and storage was part of the applied test program.

The detailed activities were the following:

- **Non-Operational TV Test**
  - 34 days test duration under vacuum
  - Temperature range -30°C – +50 °C
- **Operational TV Test**
  - 5 days continuous operation in vacuum
  - Mechanical and thermal I/F variation
- **Operational long time ambient Test**
  - >8 weeks of operation in lab
- **3 years of storage**

During all test activities the performance of the running laser was monitored and key performance requirements characterized at dedicated steps during the test campaign end.

The applied variations of the operational thermal environment were by factors larger than the predicted BOL to EOL variations in a space mission. Energy, pointing and divergence were monitored during the test campaign. The results clearly show the high robustness of the presented laser design against thermal disturbances. Even during not flight representative transitions, all performance parameters remained always in peak-to-valley distribution within the most demanding "short term" (=1.4 s) ranges required by the FULAS specification, which was fully derived from ATLID.

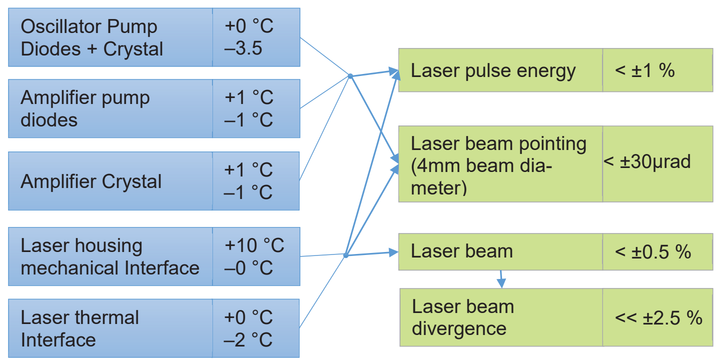

Figure 2-6: Overview of thermally induced laser performance sensitivity of the FULAS laser

In summary it could be demonstrated that the measured values show a nearly completely negligible lifetime performance degradation of the laser alignment.

- The FULAS Oscillator was aligned in autumn 2015
- No realignment was performed since this date
- No adaptation of operational set point was performed
- **The performance variation after seven years is lower than the measurement uncertainty given of the standard laboratory measurement equipment calibration accuracy**

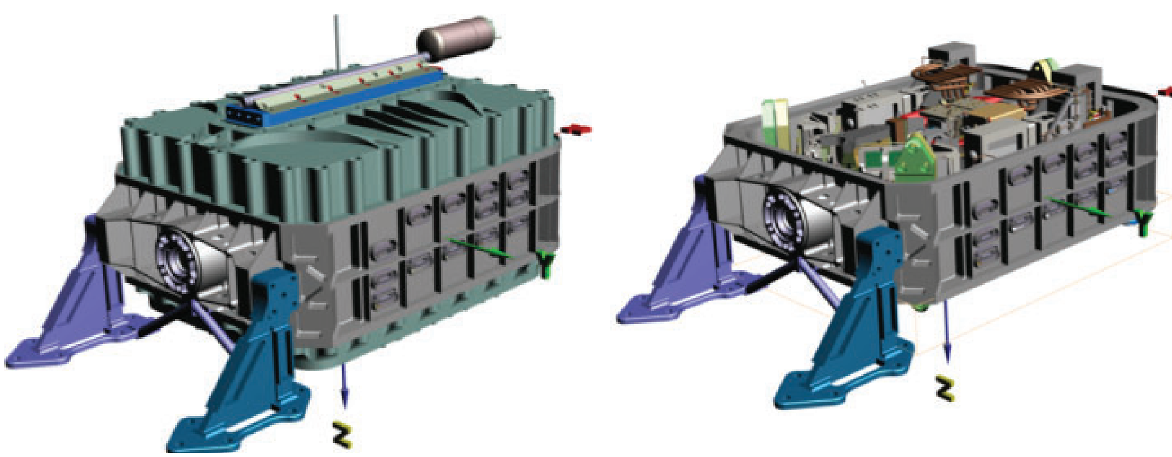

Figure 2-7: AEOLUS2 Laser PDR design – left closed housing with payload Loop-Heat-pipe / right open LASH with mounted LASO

2.3 AEOLUS 2 implementation

All key FULAS and Merlin design aspects that guarantee the laser performance and especially the long term stability of the laser performance have been transferred to the new laser (see Figure 2-7). The much higher optical pulse energy required for the mission has led to some modifications compared to the former designs:

- The external isostatic mounting was replaced by an optimized design to guarantee the best possible compromise between negligible stress towards the payload interface and a highest possible Eigen frequency of the laser
- The electrical and optical interfaces are distributed over three sides of the laser housing in a further iteration to optimize the internal harness routing.

In addition all Lessons learnt from the former projects were used to further optimize the next generation of such lasers. The main focus of the optimization is in the field of the thermal management of the laser. Due to the fact that the power consumption of AEOLUS2 is higher than in FULAS and MERLIN, a most effective heat-rejection system has been introduced.

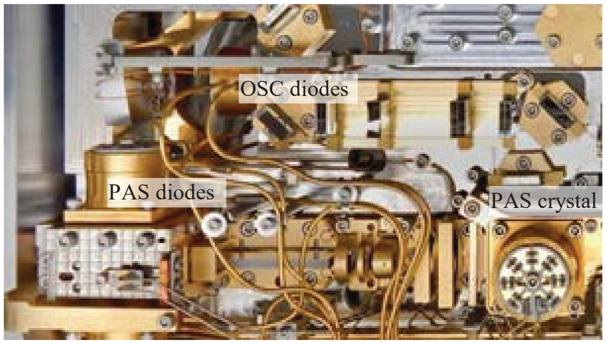

Figure 2-9: FULAS LoopHeatPipe concept

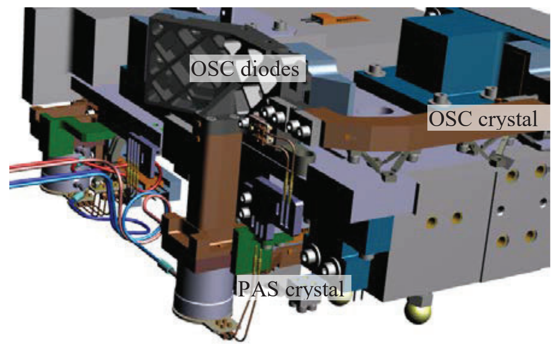

Figure 2-8: MERLIN thermal structure

The FULAS concept was based on direct rejection of the thermal load from the source by dedicated loop-heat-pipes (see: Figure 2-8). These LHP were then routed through the laser housing to the laser cold plate, which is the interface for a payload level cooling system (see: Figure 2-1).
This direct contact to any source could not be used in AEOLUS2 due to the high number of heat-emitting elements.
Instead, the Merlin concept was implemented, in which the heat-emitting elements were thermally connected by metallic structures. This allows for minimizing the number of required thermal interfaces at the LASO (see Figure 2-9).
The final transport of the thermal load at this interface was realized by two Mini-LHP directly routed through the laser housing towards the radiator, to maximize the efficiency of the thermal control system in space environment (see Figure 2-10). The drawback of this concept is its complexity in terms of AIT operations at the laser and payload level.
Specifically, at laser level the thermal control system is driving the LASH AIT due to the need to integrate the loop-heat pipes and the associated feedthroughs in the housing manufacturing sequence.

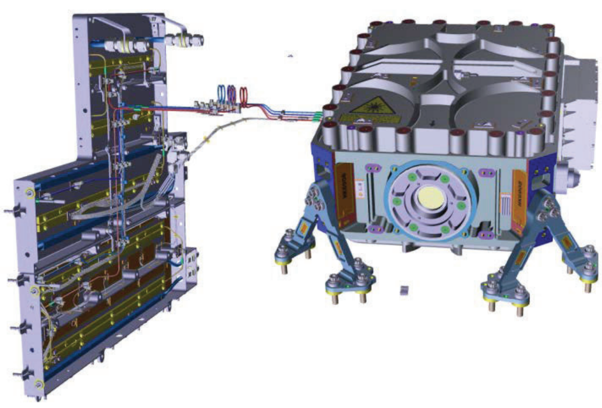

Figure 2-11: Merlin Laser with direct connected radiator

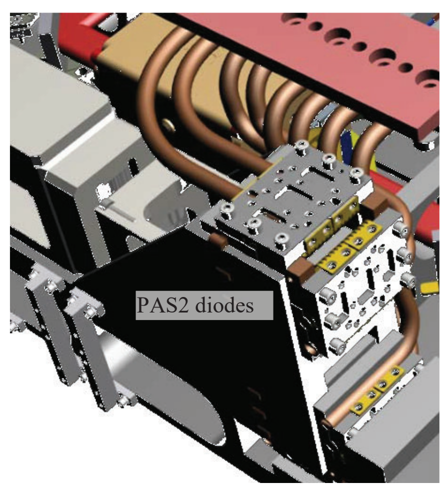

Figure 2-10: ALTA PAS2 pump diode with preliminary routing of Cu_H2O HP

At payload level, the complex thermal control system of the laser with the radiator has to be handled with a high accuracy, as the relative positions of the different elements cannot deviate by more than a couple of mm. This requirement is caused by the need to avoid plastic deformations of the steel pipes in between.
Due to the much higher thermal load of AEOLUS-2 this full metallic structure concept as used in Merlin would require very heavy structures with a not acceptable mass increase.

Therefore a solution was devised in which such solid structures are exchanged by copper-water heat pipes. The copper-water heat pipes have a ratio of thermal conductance to mass which is one order of magnitude higher than that for metallic structures (see Figure 2-11).

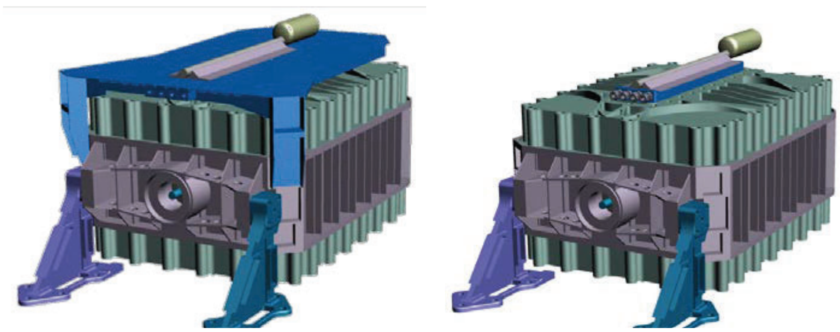

Figure 2-12: ALTA Laser
left: TCS at PDR right: new TCS

With use of this thermal hardware it was possible to realize at LASO level a reduction to only two thermal interfaces with nearly identical thermal load. These two interfaces will be used for rejection of the heat load with the laser TCS.

In a first iteration of the present AEOLUS-2 design, a concept similar to FULAS, with dedicated top-mounted cold plate, was developed.
As an output of the further iteration of the laser optimization for mass reduction a smaller, more compact concept was identified.
A major design aspect was to secure a full compatibility of the TCS with the performance and interface needs of the LASO and the payload.
Beside the mass reduction, this new concept has strongly relaxed the constraints for the laser level AIT.
The new TCS concept is independent from the LASH manufacturing and can be mounted at the end of the laser final integration activity in which the fully aligned LASO will be integrated in the LASH.

3. CONCLUSIONS

The design concept of the ALTA laser is leveraging the proven design of the FULAS/MERLIN laser, which has demonstrated its outstanding thermomechanical performance. 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 results of former test campaigns it could be demonstrated that the concept is meeting all performance stability goals thus enabling reliable operation at high measurement precision of a future instrument, With the accomplished component and subassembly qualifications achieved in the frame of the MERLIN the underlying technology has shown its maturity and flightworthiness.
The new laser thermal control system is optimized to minimize mass and reduce schedule and AIT risk during the overall laser manufacturing sequence.

4. ACKNOWLEDGEMENTS

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