

The LISA Laser System – development approach, performance analyses and overall design

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ABSTRACT

The Laser System for the future space-based gravitational-wave detector Laser Interferometer Space Antenna (LISA) is a key part to enable the required mission performance to detect gravitational waves by laser interferometry. The to-be-observed distance changes are in the picometer region, translating into highly demanding performance requirements for the laser system. SpaceTech has developed, built and tested an EM of the Laser Head for LISA in the past and is now developing the flight hardware of the laser system for the mission as prime of a European consortium to develop and build the system in line with the mission programmatic and technical requirements.

Key and driving performance requirements are the optical output power of 2 W in single frequency in fundamental gaussian mode at the interface to the optical bench, while meeting the required RIN, frequency noise and phase-sideband fidelity over the full science measurement band. Together with the launch environment, the lack of suitable space qualified photonic components, the spacecraft configurational requirements and the tight schedule for the development, the undertaking requires an efficient breakdown into the subsystems, a well defined yet programmatic qualification approach and a quick ramp up of the whole consortium team.

The laser system has been structured into functional subsystems, including a redundancy scheme to meet the mission reliability demands. The Laser Head EM has been put back into operation and completed a second full performance test campaign at CSEM, confirming the results of the previous test campaign at SpaceTech for meanwhile more than 12,000 hours of operation. The selection of photonic components is in progress, and the details of the qualification program are in iteration.

Keywords: LISA mission, LISA Laser System, fibre amplifier, single frequency, gravitational waves

1. INTRODUCTION

The future space-based gravitational-wave detector Laser Interferometer Space Antenna (LISA) will detect gravitational waves by laser interferometry. For this space-based gravitational-wave detector laser light from three spacecraft will form an equilateral triangle, where each side of the triangle is about 2.5 million kilometers long. This constellation will follow the Earth by its orbit around the Sun. Gravitational waves passing through this laser triangle will slightly distort the arm lengths between the free-falling test masses located at the center of each spacecraft. The to-be-observed changes in the science measurement band between 1 Hz and 0.1 mHz, translate into the $\text{picometer}/\sqrt{\text{Hz}}$ region [1] therefore very high stability and low noise requirements apply to the complete interferometer system in this frequency range, for the laser system, the requirements range into the multi MHz range.

Onboard each LISA spacecraft there will be one Laser System consisting of two Laser Assemblies and one Frequency Reference System. Each Laser Assembly is comprised of two Laser Heads and two external power monitors for each Laser Assembly: one in nominal and one in cold redundant operation of each of the two interferometer arms that each of the spacecraft operates [2].

Parallel developments on ESA and NASA sides were performed in the past. On ESA side several development activities at CSEM, LusoSpace, SpaceTech [2] resulted in the Laser Head EM from the SpaceTech led consortium [3][4], either achieving or coming close to the key needed performance requirements in 2024. Likewise, the development of the Frequency reference system was pursued in Europe in several activities [5][6][7], also in conjunction with the similar needs of the Laser Tracking interferometer of NGGM [8].

With mission adoption in 2024 the development of the Laser System became part of NASAs contribution to LISA. As part of risk mitigation activities and to safeguard the mission launch schedule, ESA has reopened the development and awarded SpaceTech a contract to develop a European solution for the LISA Laser System in March 2026.

Below we present the overview of the LLS, the development approach, including model philosophy and photonic components qualification approach, the key performance requirements and the results achieved in the test campaigns as well as the LLS design concept that is pursued to provide QM and FM models of the LLS in line with the mission development timeline.

2. LISA LASER SYSTEM OVERVIEW

The LISA Laser System (LLS) on each spacecraft consists of four Laser heads (LH1N, LH1R, LH2N, LH2R), two for each interferometer arm, one Frequency reference system (FRS), consisting of an electronics units (FRS-E) and an optical unit (FRS-O), and four power Monitors (PMON), each connected to one of the laser heads.

The LLS is a distributed system in the satellite. The four laser heads are mounted on the outside satellite panels, the FRS is mounted on the inner structure of the satellite, and the power monitors are mounted on the optical benches of the payload core assembly subsystem in the central part of the satellite.

The system is largely redundant, with one laser head operated in each arm, and one frequency reference system out of three in the three-satellite constellation in operation only at any time, providing the frequency reference for all operated lasers. Each laser head is capable to be locked to the FRS, all others are then offset locked to this one reference laser, controlled by the phasemeters which interface all laser heads. The power monitors are utilized for RIN stabilisation of the laser head signals on the optical benches, close to the test masses. They contain 2 photoreceivers which are operated simultaneously, one in-loop for the actual power stabilisation, one out-of-loop to measure the remaining RIN of the system. In case of a photoreceiver failure, the out-of-loop one can be used for in-loop control. Figure 1 shows the functional blocks and the preliminary accommodation of the laser heads and the FRS in the satellite (red boxes).

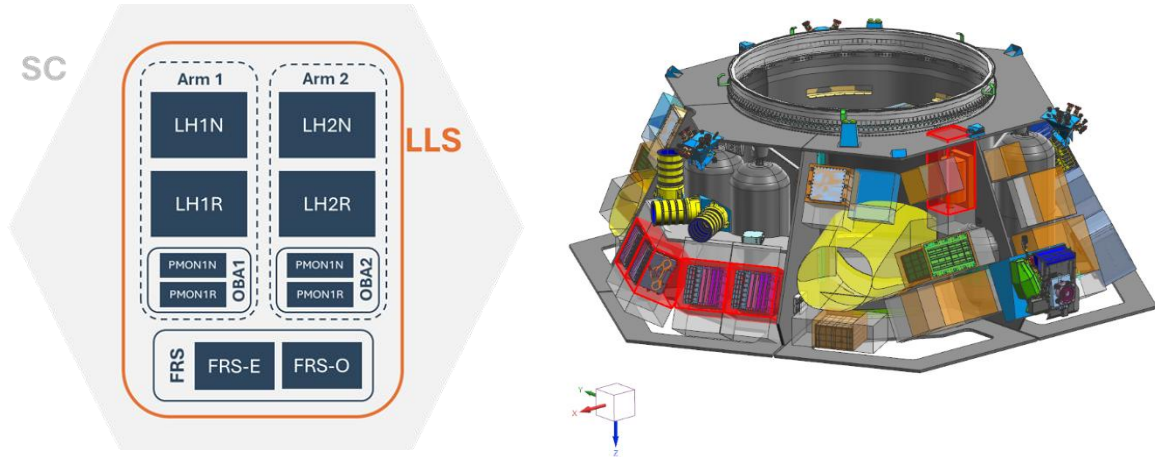


Figure 1: Left: Functional blocks of the LISA laser system; Right: preliminary accommodation of Laser Heads and FRS in the Satellite (Credit: OHB)

3. DEVELOPMENT APPROACH

The development approach builds on the “Gravitational Wave Observatory Metrology Laser” activities which resulted in engineering models for the laser head and an elegant breadboard of the frequency reference system. However, the PMON is a new development. With the laser head EM vacuum operation has been demonstrated [3] and the achieved TRL level is considered as TRL 5. At the start of the flight hardware development presented here, an additional performance

verification campaign of the GWOL EM at CSEM has been performed, see section 5. Together with the test data from the previous activity, this allows for an evaluation of the existing laser head design in terms of performance and identification of necessary adaptations. For the FRS, the LLS can benefit from the development of the optical cavity of NGGM, which will achieve EQM status of the optics unit end of 2026 in the frame of the NGGM mission and is subject to very similar requirements. The FRS electronics unit development starts at TRL 4, building on the former pre-developments.

The overall mission schedule and the delayed continuation of the European laser system development drives the development schedule and the model philosophy. A development flow based on EBBs for selected sub-assemblies, followed by a qualification model and the flight model(s) of the laser system is foreseen.

One essential aspect both in the system design as well as in the later AIT process is the need to assemble and test 4 laser head flight models, and integrate and test those into a full LLS in the time of 6 months. For comparison, the EM took about 1 year for assembly and initial testing. For this small series manufacturing the laser head design will be adapted to allow for a higher level of pre-assembly of the individual unit frames, exchangeability in case of issues and the concept of an assembly flow on several work benches, to manufacture multiple laser heads in parallel in a staged approach. We will make use of our experience in the series production of solar arrays gathers since 2016 in establishing a stable production of the LLS.

Apart from the challenging overall performance of the laser system in general, one of the key topics is the availability of the required photonic components. The components are in many cases not readily available in space-compatible designs and not using well-controlled space-suitable processes for manufacturing. During the pre-Development activities several commercially available photonic components, that have been partially used for the GWO LH EM, have been screened for performance, environmentally tested (radiation, temperature, vacuum, launch loads and partially long-term testing and DPA). This screening provided valuable insights into the use of purely commercial components for use in LISA. Main findings include:

- The basic setup of many components is promising for use as a good basis for LISA.
- A multitude of issues in standard devices, like poor wire bonding, chipped out optics, poor lid welding, not met hermeticity claims, and device failures of single units during environmental testing.
- Significant quality and even internal design variations between units ordered in one batch.
- Obsolescence of many parts between 2022 and today due to updated or new designs and a major shift of photonic components to outside of Europe and USA.
- Unlike experiences at high pulse power and shorter laser wavelengths no general need for hermetic housings for the photonic components was identified for the LISA wavelengths and power level in the frame of the evaluation programme (and also the laser head engineering model testing, see below), with the exception of the pump diode modules at 978 nm, where hermetic housings remain considered to be needed.

Based on these findings, the photonic components qualification approach is currently under definition by STI in cooperation with ESA. The general approach is to:

1. Rely on available space qualified components wherever possible, which is only possible for a few components.
2. Select component types not available qualified from the evaluation campaign from companies with a preference of manufacturing in Europe and only from manufacturers who have the capability to manufacture the required amount of components in one batch under increased quality control and potentially delta designs, where a need for a design change for LISA was identified.
3. Perform a pre-evaluation of photonic components that have not been part of the former evaluation campaign, e.g. due to obsolescence.
4. In case of a remaining risks on the parts suitability, choose 2 different suppliers for selected components
5. Procure all photonic components, where not established space qualified devices are available, in one single batch from QM the full FM quantity to allow for a lot acceptance testing and batch qualification program early in the development.

Considering the required quantity of 1 QM, 12 FM and additional flight spares of the laser head, approximately 3000 photonics are expected to enter the batch qualification program for the laser head alone, in addition to the components in the FRS and PMONs.

Considering the increasing number of laser systems in space missions and the shift of the laser industry towards component manufacturing, in the past a strength of European companies and institutes, to outside of Europe, the maintaining of the capability of Europe to produce space suitable photonic components is considered a challenge by us and initiatives to maintain/develop this field in Europe are considered important.

4. KEY PERFORMANCE REQUIREMENTS AND ANALYSES

The Laser Head shall provide 2W of single-frequency, linearly polarized optical power at a center wavelength of 1064.5 ± 0.05 nm, with a polarization extinction ratio above 20 dB and stringent requirements on spectral purity. In addition to the fundamental optical characteristics, the interferometric measurements place demanding requirements on relative intensity noise (RIN), frequency noise and phase sideband fidelity over a wide frequency range. Together with the fiber length within the laser head and along the delivery path to the optical bench, the noise requirements represent key drivers for the LLS architecture and design.

Relative Intensity Noise (RIN)

The output power stability, expressed as RIN at the output of the delivery optical fiber and evaluated over the nominal mission lifetime, is specified for a frequency range from 100 μ Hz to 3 GHz as follows:

$$S_{RIN}(f) = 1 \cdot 10^{-4} \cdot \sqrt{1 + \frac{0.5 \text{ mHz}}{f}} \text{ for } 100 \mu\text{Hz} \leq f \leq 100 \text{ Hz}$$

$$S_{RIN}(f) = 2 \cdot 10^{-6} \text{ for } 100 \text{ Hz} \leq f \leq 3 \text{ MHz}$$

$$S_{RIN}(f) = 3 \cdot 10^{-8} \text{ for } 3 \text{ MHz} \leq f \leq 3 \text{ GHz}$$

Since the requirement applies at the output of the delivery fiber, the entire optical path from the Laser Head to the optical bench must be considered. Therefore, the RIN requirement drives not only the intrinsic intensity-noise performance of the Laser Head, but also the power stabilization concept, distributed in the spacecraft. The external power monitors located on the optical benches provide the signals for active power stabilization and for monitoring the residual RIN at the relevant system interface.

Frequency Stability

In reference mode, the frequency-noise requirement defines the maximum allowable frequency noise during the acquisition and locking of the laser frequency to the Frequency Reference System (FRS) cavity in science operation, over a frequency range from 0.1 mHz to 60 MHz as follows:

$$S_v(f) = 30 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(2 \frac{\text{mHz}}{f}\right)^4} \text{ for } 0.1 \text{ mHz} \leq f \leq 1 \text{ kHz}$$

$$S_v(f) = 3.75 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(8 \frac{\text{kHz}}{f}\right)^2} \text{ for } 1 \text{ kHz} \leq f \leq 5 \text{ MHz}$$

$$S_v(f) = 10 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \text{ for } 5 \text{ MHz} \leq f \leq 60 \text{ MHz}$$

The frequency noise requirement is a key driver for the frequency stabilisation architecture of the LLS. In reference mode, one laser is stabilised to the FRS, while the remaining operated lasers are offset locked to this reference. Consequently, the required frequency noise performance directly affects the performance requirements of the FRS and the associated frequency control scheme.

Differential Phase Noise

The phase sideband fidelity is defined by the RF modulation noise requirement, which restricts the LLS contribution to the phase noise between the optical carrier and the 2.4 GHz sidebands, as follows:

$$S_{\phi}(f) = 60 \cdot \left(1 + 7 \cdot \frac{10^{-2}}{f}\right) \frac{\mu\text{rad}}{\sqrt{\text{Hz}}} \text{ for } 0.1 \text{ mHz} \leq f \leq 1 \text{ Hz}$$

These high frequency requirements correspond to contributions of approximately 0.5 pm/ $\sqrt{\text{Hz}}$ for carrier-to-carrier phase extraction and 10 pm/ $\sqrt{\text{Hz}}$ for sideband-to-sideband readout. This places stringent constraints on the phase modulation generated within the laser head and on the additional carrier-to-sideband phase perturbations introduced along the subsequent optical path.

Fiber Length

The lengths of the fibers within the laser head and along the delivery path to the optical bench represent an additional design consideration. At the required optical output power, fibers length directly affects the onset of stimulated Brillouin scattering (SBS). Therefore, short fibers lengths are desirable in order to maintain sufficient SBS margin.

In addition to the SBS constraint, fibers length directly affects the stability performance achievable with the LLS. Environmental perturbations along the fibers path can introduce intensity, phase, and polarisation fluctuations, thereby affecting RIN and phase-sideband fidelity, and contributing to the overall frequency stability of the optical signal. Keeping the optical fiber paths as short as possible reduces these contributions and supports compliance with the key noise requirements discussed above. Consequently, the fiber lengths within the Laser Head and along the delivery path need to be minimised within the constraints imposed by the Laser Head layout, spacecraft accommodation, and optical interfaces.

5. LASER HEAD EM DESIGN AND EM TEST RESULTS

The GWO EM laser head consists of five interthreaded compartments, where the baseplate (lowest compartement) is the mechanical and thermal interface towards the S/C, containing all components with high thermal dissipation, such as the Seed Laser, the amplifier pump diodes and the dc/dc converters. The higher compartments mainly contain the fiber amplifier stages with associated proximity electronics. In the EM laser head already hosts all subelements needed for the later flight models, namely the NPRO Seeder, the two-stage fiber amplifier with the pump diode modules, all PCBs to operate the laser head in the mission thermal environment defined by the time of the development up to 2024. In

The EM provides >2W at the main output fiber towards an optical bench and a small fraction of light to a cavity. The total mass of the EM is 10.2 kg (harness excluded) and has a dimension of 302 x 302 x 196 mm³. Further data on the EM can be found in [4].



Figure 2: Fully assembled EM laser Head at STI (left) and inside the vacuum chamber at CSEM (right)

In the following figures the test results of RIN, frequency noise and phase sideband noise for both test campaigns are depicted. The test campaign at STI took place from Oct 2023 until April 2024. The Test campaign at CSEM started in

April 2026 and ended in June 2026. For all the measurements the EM laser head was operating at $\geq 2\text{W}$ output power, frequency stabilized to a cavity, 2.4 GHz sidebands are modulated onto the EOM and the output power is stabilized. This setup is close to the later science mode in the mission. For the unstabilized frequency stability spectrum the lock between laser head and cavity is not established. For the presented measurements the laser head was operated at 21.5°C interface temperature.

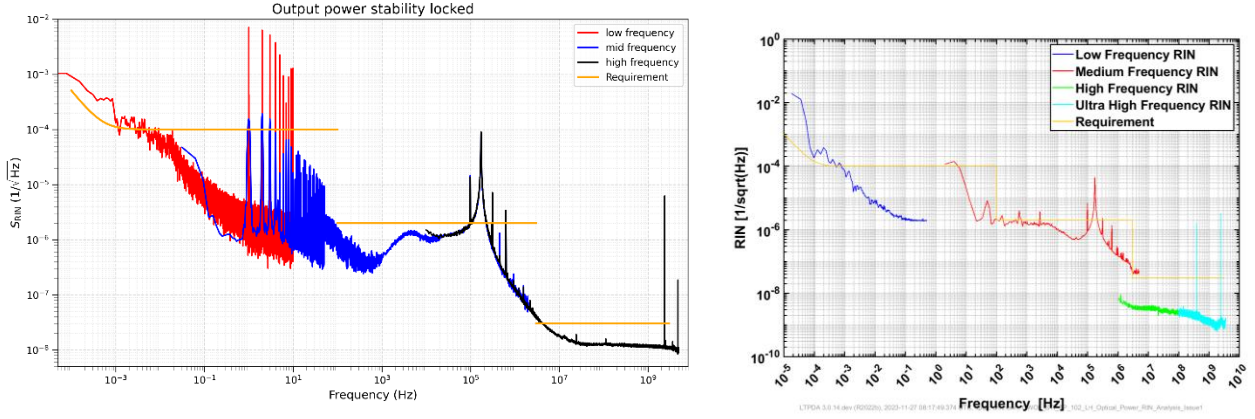


Figure 3: Comparison of full RIN spectra from test campaign at CSEM (left) to STI (right)

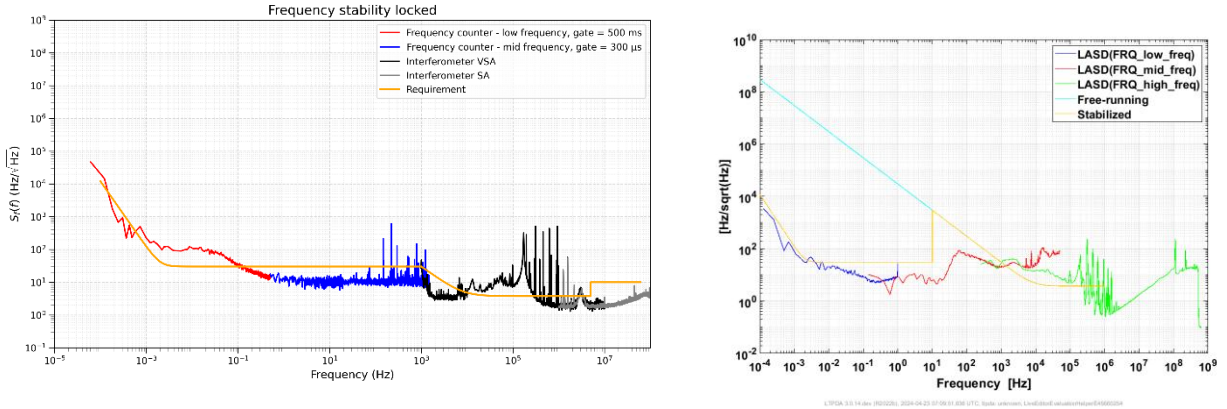


Figure 4: Comparison of full frequency stability spectra (laser head locked to cavity) from test campaign at CSEM (left) to STI (right)

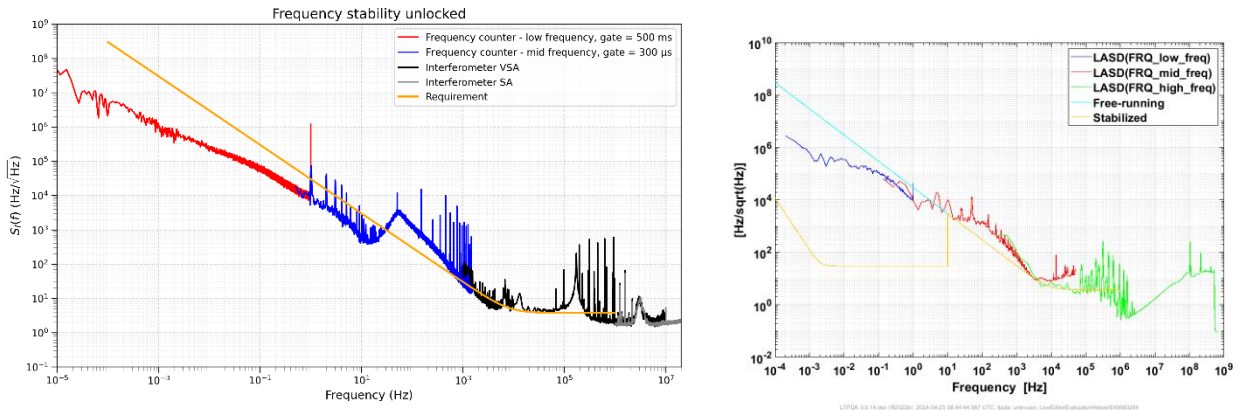


Figure 5: Frequency stability spectra (laser head free running) from test campaign at CSEM (left) to STI (right)

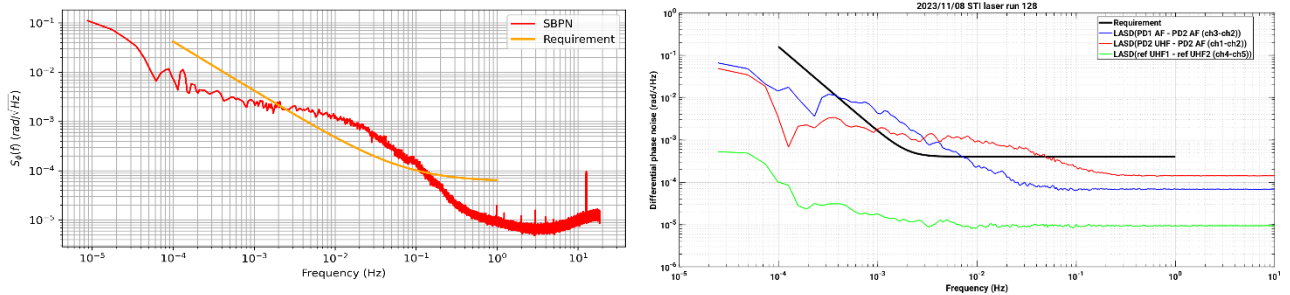


Figure 6: Comparison of full frequency stability spectra (laser head free running) from test campaign at CSEM (top) to STI (bottom)

Please note that the requirement for the Phase Sideband Noise and the locked frequency stability have changed between both test campaigns. Comparing the measurements for both test campaigns, we can state that the results in the two different test setup are very similar to each other. At the same time, the observable deviations in the measurements are being investigated, to get a better understanding, what is driven by the test setup and environment and what is coming from the laser system itself, including potential performance changes between the two test campaigns. Specifically, the RIN region around 4 mHz to 100 Hz shows prominent peaks in the measurements performed at CSEM. The main root cause is still under investigation, but it is clear that this originates from the laser head, potentially with part of the EGSE that has an update rate of 1 Hz.

Even though not all requirements were fully achieved with the GWO laser head EM in all frequency ranges, the results are at least close to the requirements. To meet the requirements in the subsequent models, improvement on the EM laser head is currently ongoing and involves thermal management and control electronic design.

The EM laser head was stored between both test campaigns for 2 years in a controlled environment. The measurements show no significant performance degradation after this time and setting back the EM in operation was without any difficulties. At the end of the performed test campaigns at STI and CSEM the EM has reached a total time in operation > 12.000 h from which > 6.000 h are within a vacuum environment.

6. LASER SYSTEM DESIGN

Figure 7 gives an overview of the LLS design. The laser head (LH) consists of the main oscillator based on an NPRO and two fiber amplifier stages. After the first stage light is split off and directed to the frequency reference system (FRS) based on a stable optical cavity.

If the laser head is operated in “reference” mode, the FRS controls the laser frequency while in “transponder” mode the phasemeter (PMS) provides the frequency control signal. Since all laser heads on each spacecraft are connected to the FRS, an optical switch is needed to block the light path to the FRS from the laser head operated in transponder mode. Sidebands and PRN signals are modulated with the EOM after the first stage amplifier. On the optical bench, a part of the light from the LH is split-off and guided to the photodetectors inside the power monitor (PMON). The PMON signal is used actively to stabilize the RIN at the position of the optical bench via the second fiber amplifier stage. The first amplifier stage has an internal RIN stabilization.

A similar mechanical design as for the GWOL EM, consisting of multiple module frames with optical and electrical components, is foreseen. Adaptions due to thermal stabilization needs as well as design updates will be made. As a parallel activity, a hermetic housing option is currently investigated. The hermetic housing will be required if vacuum operation of the optical components is ultimately not possible, see section 3 on photonic component qualification.

The FRS development is taking advantage from the parallel development of the Laser Tracking Instrument (LTI) of NGGM, with similar performance as required for LISA. The electronics of the FRS as a stand alone unit are a new development, as NGGM has those electronics included in the LTI ICU.

The whole development is performed by a consortium lead by SpaceTech with subcontracts for the Seed laser, the FRS, the PMON and the photonic components qualification program to leading European Companies and institutes.

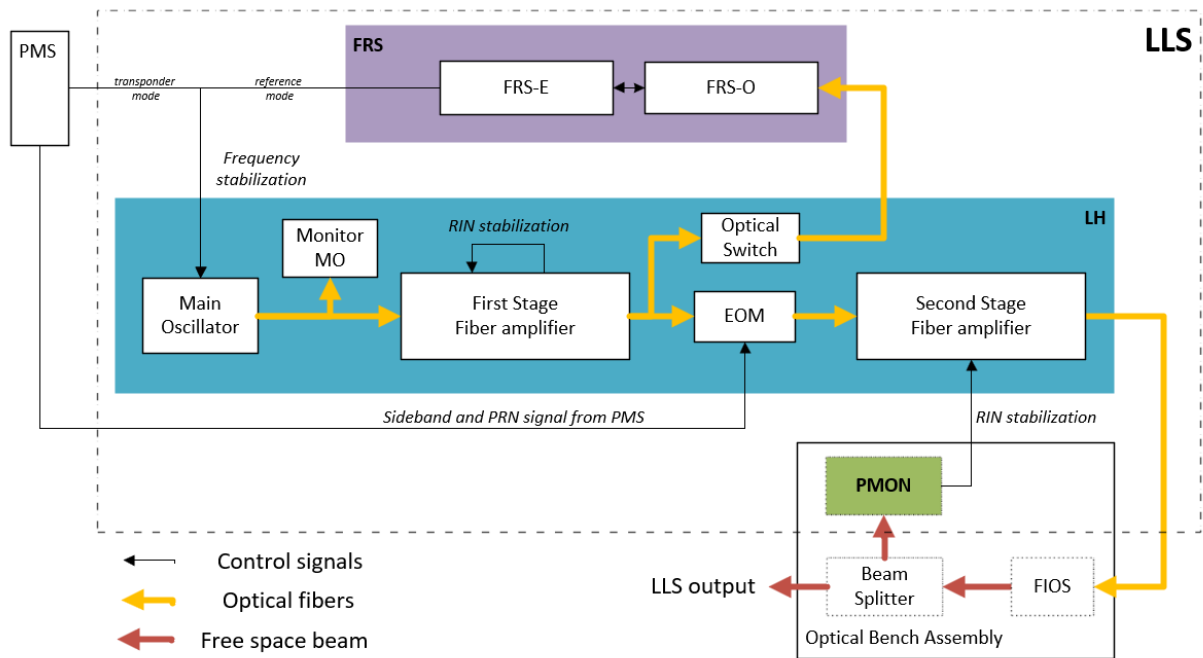


Figure 7: Block diagram for the LISA laser system (LLS) with sub-units and some relevant interfaces. The frequency reference system (FRS) consists of an optical assembly (FRS-O) and an electronic part (FRS-E). The power monitor (PMON) is located on the optical bench. Light from the LH is coupled to the bench via the fiber injector optical sub-assembly (FIOS), split, and a part directed to the PMON.

7. SUMMARY

The European LISA Laser System development, based on the heritage established during the GWO activities, extend the pre-developments towards qualification and flight hardware. The additional test campaign of the EM laser head performed at CSEM in 2026 reproduced the overall performance achieved during the previous campaign at SpaceTech, leading to an accumulated more than 12,000 hours or 1 ½ years of operation. The parallel development of the optical frequency reference in the frame of NGGM advanced the TRL also for the LLS. The further development will center on further improvements to fully meet the LISA performance requirements, to adapt to the system requirement changes, the final selection and qualification of photonic components, the system level qualification and ultimately the small series production to meet the mission timeline.

The whole development is performed by a consortium of European companies and institutes with proven expertise in the field of highly stable laser systems for space and specifically LISA to ensure the overall performance in the required time frame.

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