DEVELOPMENT OF THE US LISA LASER SYSTEM

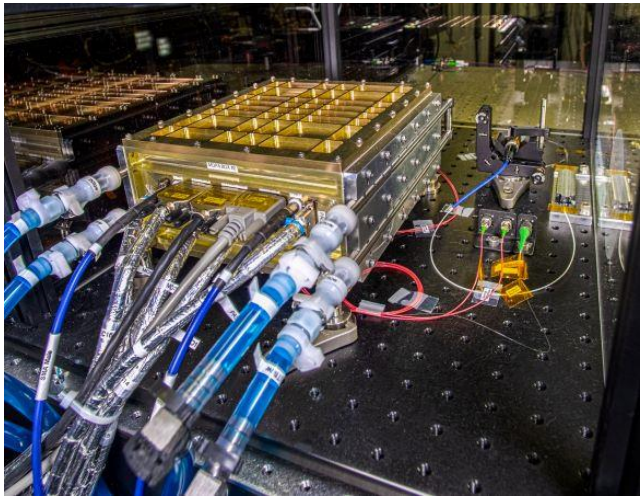
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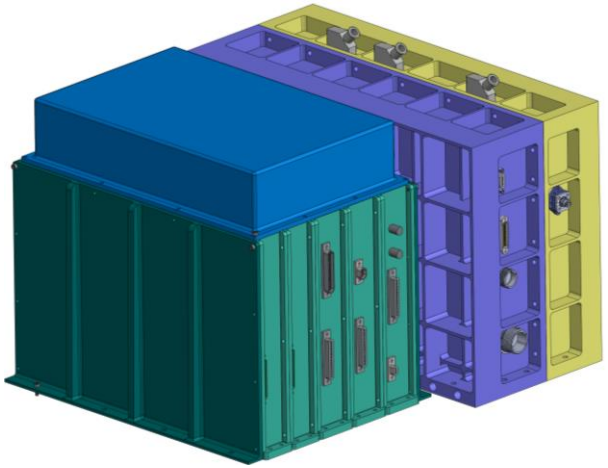
27 JULY 2022

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4. **Frequency reference system (FRS)**
5. **Power monitor detector (PMON)**
6. **Reliability**
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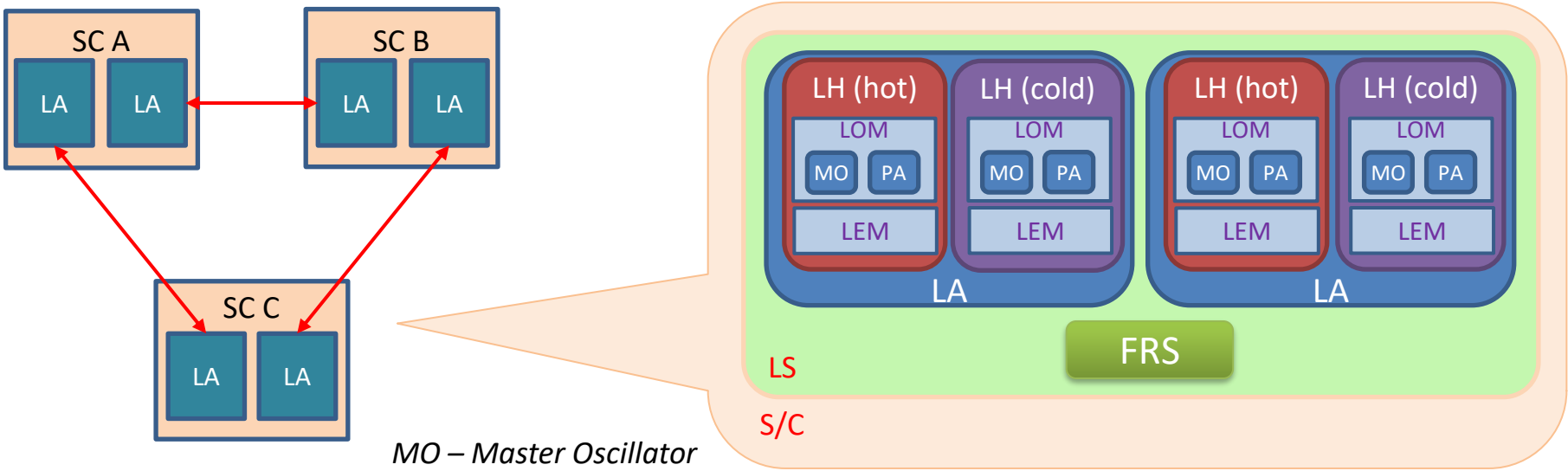
TRL 4 LOM



TRL 6 LEM and LOM design

1. INTRODUCTION

- **Laser: possible US contribution to LISA**
  - US laser work officially started in ~2017
    - Currently transitioning from TRL 4 to TRL 6
  - TRL6 LOM delivery to ESA for evaluation: early summer 2023
  - Adoption review and decision: late 2023 ~ early 2024
- **12 laser heads in constellation**
  - 1 laser system (LS) per S/C
  - 2 laser assemblies (LA), 1 frequency reference system (FRS, cavity) per S/C
  - 2 “hot” and 2 “cold” laser heads (LH) per S/C



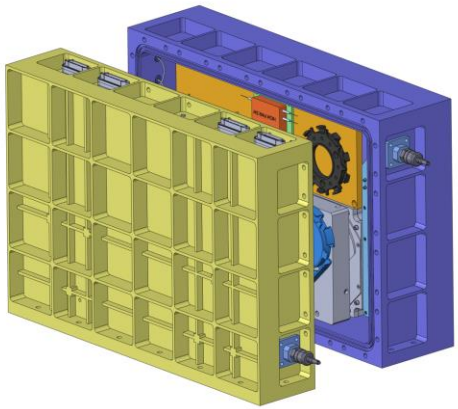
MO – Master Oscillator
PA – Power Amplifier

TOP LEVEL LASER REQUIREMENTS

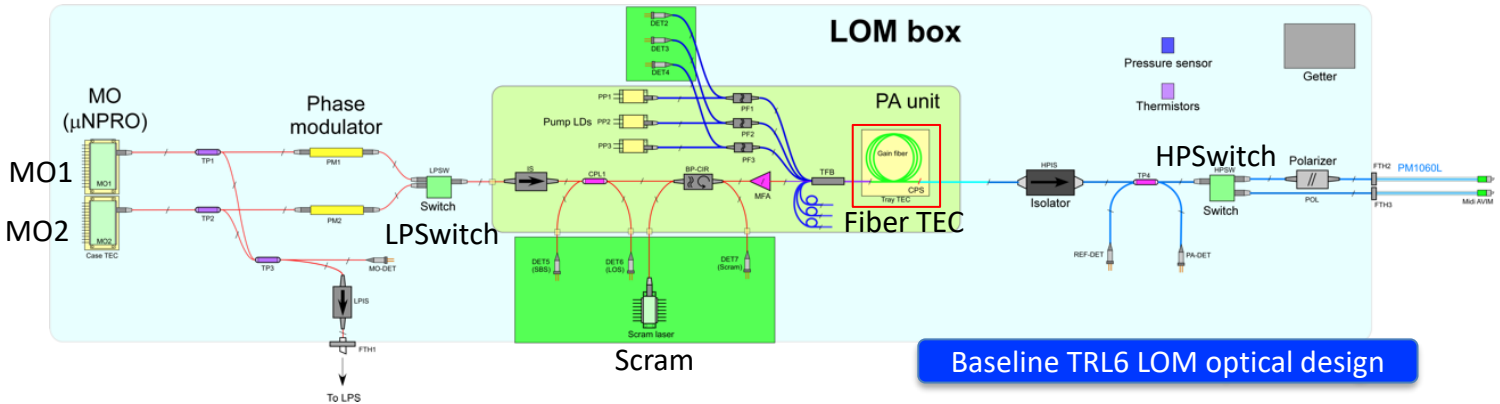
- **General requirements**
  - Dimensions: 330 × 330 × 250 mm^3 (TBR : 332 mm x 414 mm x 250 mm CBE with 20% margin)
  - Mass: 12kg (TBR : 19.2kg CBE with 20% margin)
  - Dissipated power: <75W (TBR : 86W nominal CBE with 20% margin)
  - Operating temperature: 20±5°C (TBR)
  - Non-operating temperature -20°C to +40°C (TBR)
  - Vibration, shock, radiation, etc.
- **Optical requirements**
  - Output Power >2W on optical bench (OB) at end of life (EoL)
  - Wavelength 1064.50, -0.05/+0.10 nm
  - Polarization extinction ratio (PER) >20dB (TBC)
  - Noise requirements (Frequency noise, intensity noise, RF phase noise)
- **Lifetime requirement: 10~16 years**
  - 6 years on ground with ~1 year for integration and testing, plus 5 years (TBC) of storage
  - 1.5 years (TBC) OFF state in operational environment (cruise phase)
  - 5 (TBC) years continuous operation in nominal science mode (nominal mission lifetime)
  - 11 (Goal) years continuous operation in nominal science mode (extended mission lifetime)

2. LASER OPTICAL MODULE (LOM)

- **Master Oscillator Power Amplifier (MOPA)**
  - Start from low noise oscillator, amplify it with relatively simple amplifier stage
  - Multiple internal redundancies to meet lifetime requirement
    - Two Master Oscillators (MOs): MO1 and MO2.
      - Each MO has two pump LDs (hot redundant)
    - PA uses three pump laser diodes (cold redundant)
      - Each pump laser diode has three internal emitters
- **Protection mechanisms**
  - "Scram" laser to protect the amp in the event of MO loss of signal
  - Fast pump shut off, monitor ports to detect lasing
- **Pressurized "clamshell" box**
  - To allow for streamlined build : MO slice and PA slice can be built separately
  - Single thermal/mechanical interface : mechanical stiffener from outside



MO slice and PA slice



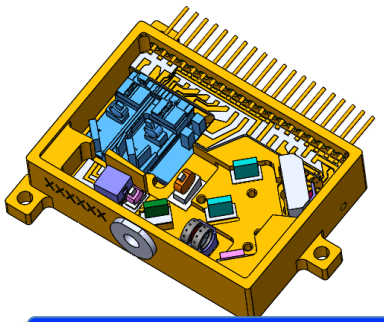
Baseline TRL6 LOM optical design

2.1. MASTER OSCILLATOR

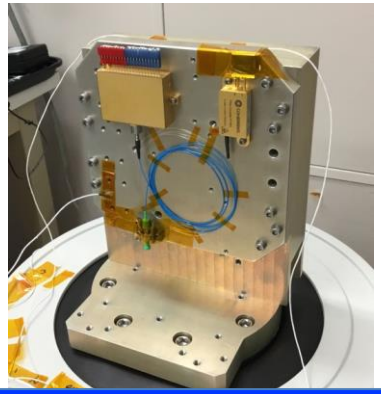
- **µNPRO status summary**
  - Basic process established with ~3 process development units
  - AVO Photonics is finishing up first ~9 EM-Q (qualification) units
    - Many lessons learned. Significant improvement from TRL4/5 packages.
    - Production process and workforce being established
  - Qualification tests
    - Radiation test, shock, and vibration test passed
    - Temp cycle passed (no degradation after 50C, -30C soaks)
    - Pump LD tests at EYP, pump module tests at GSFC : ongoing, looks promising
    - Long-term aging test for µNPRO package planned
  - Performance improvements
    - PZT tuning efficiency, fiber coupling efficiency, etc.
    - Low frequency noise



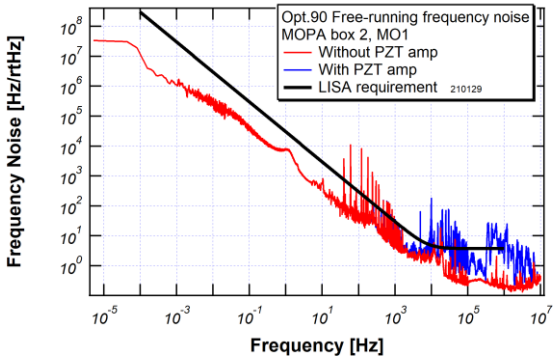
µNPRO build at AVO



µNPRO package



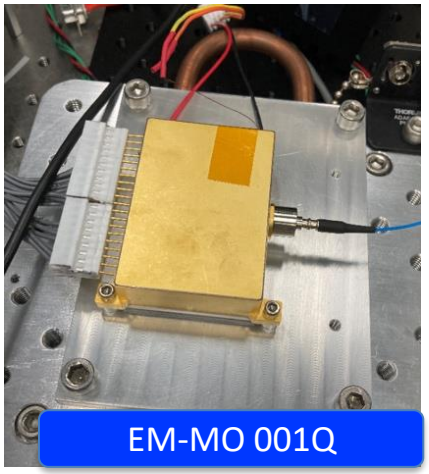
Vibration testing



Frequency noise

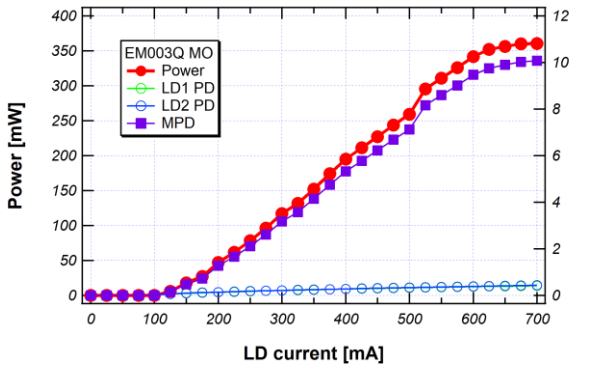
EMQ MO UNIT

- **Design changes from TRL 4/5 to TRL 6**
  - Hermetically-sealed package with getter
  - Use of solder as much as possible to minimize drift
  - More rigid mechanical design
  - Crystal redesign
  - x10 higher PZT tuning efficiency (no need for HV)
    - T. Kane et. al https://doi.org/10.1117/12.2610410
  - Dual-loop TEC for pump diode
  - Improved fiber-coupling efficiency
  - Procedure improvement
  - Intensive mechanical/thermal modeling



EM-MO 001Q

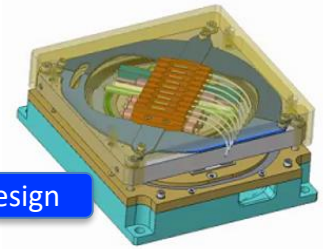
- **EMQ µNPRO package**
  - AVO Photonics: delivered 7 units by now.
    - Finalizing process to have the best performance.
  - Waiting to build EMQ #8 and 9 (final set of EMQ)
    - Some final changes (e.g. PZT metallization, mirror shape)



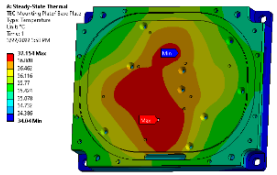
EM-MO 003Q output power

2.2 POWER AMPLIFIER

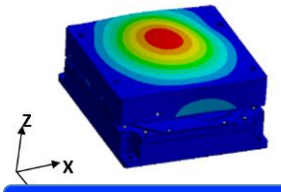
- **Status summary**
  - Main build work done at Fibertek
    - Delivered 3 TRL4 (ETU) units by 2021
  - Passed CDR on March 2022
  - Finished up TRL6 EMQ design, delivered 1st EMQ unit for evaluation.
    - Improved mechanical and optical design
    - Scram laser + detector board designed and built
    - EMQ (EDU) unit being used for additional data collection
    - Completed vibe (18.5Grms), storage and operational temp tests
    - Every component tested under thermal cycle and vibration
  - Thermal and mechanical analysis, numerical modeling
  - Reliability activity (e.g. accelerated life test) and process development



TRL 6 PA design



Thermal analysis



Vibration analysis



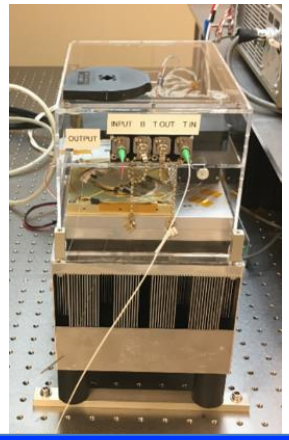
PA vibration testing

- **Design**
  - Forward pumped amplifier with 10µm double-clad Yb gain fiber
  - 3 pump LDs (2 of them are cold redundant)
  - Original mechanical design taken from CubeSat laser comm. terminal

EMQ PA UNIT

- **Design changes from TRL 4/5 to TRL 6**
  - Core coupled Scram laser enabled by the hybrid 1030nm DWDM + circulator component.
  - 4 additional optical monitoring channels
  - 3x pump optical monitoring enabled by the hybrid tap + protection filter component
  - 2x Backward monitoring both for 1030nm and 1064nm/SBS bands
  - Addition of 7 compact fiber feed thru for ruggedizing optical input and output
  - Pump lasers are changed from IPG to Coherent 976 VBG diodes
- **Further optimization**
  - Looking into longer gain fiber for higher robustness
  - Split amplifier concept as a backup

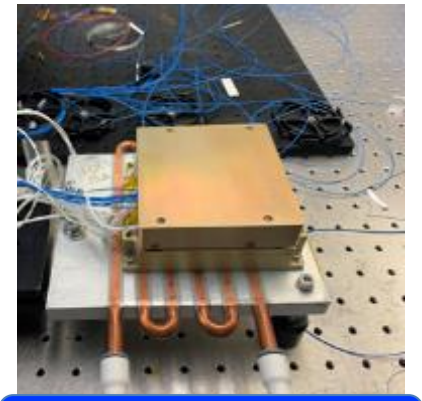




Prototype amplifier (TRL ~3)



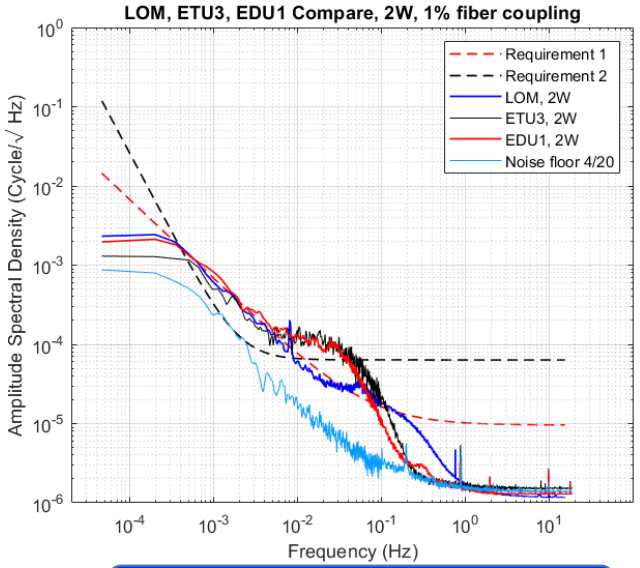
Engineering Test Unit (TRL ~4)



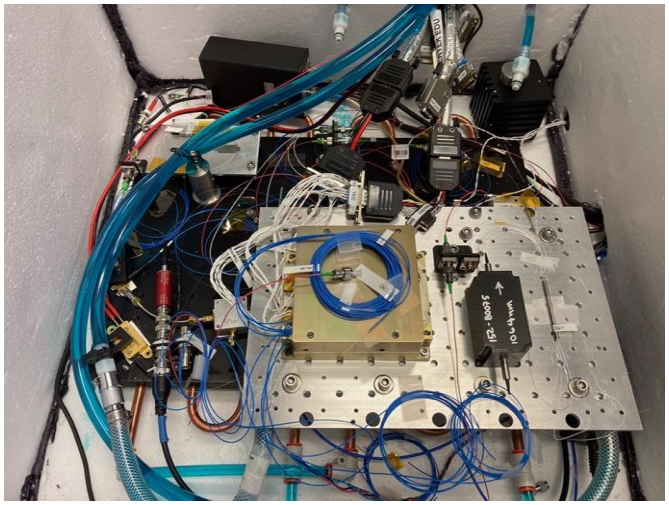
Engineering Model for Qualification (TRL ~6)

RF SIDEBAND PHASE NOISE MEASUREMENT

- **RF phase noise: key noise parameter**
  - Directly affects LISA performance
    - Not meeting the simple 1pm/rtHz allocation (New requirement being discussed)
    - Measurement itself is difficult: affected easily by environmental noise
    - Noise mechanism not fully understood
  - Dedicated studies ongoing
    - Refer to a pre-recorded talk by Xiaozhen Xu, “RF differential phase measurements of the LISA fiber amplifier”.



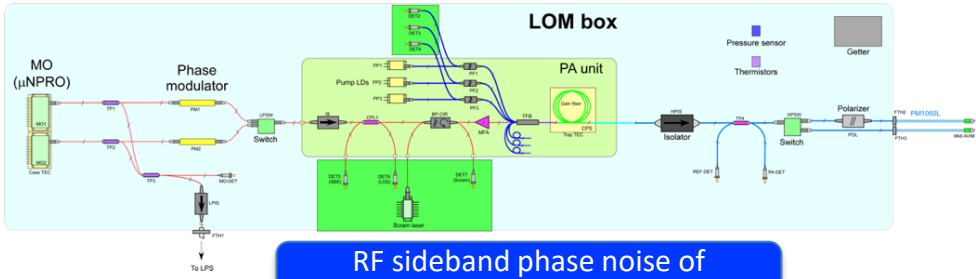
RF sideband phase noise of different amplifier models



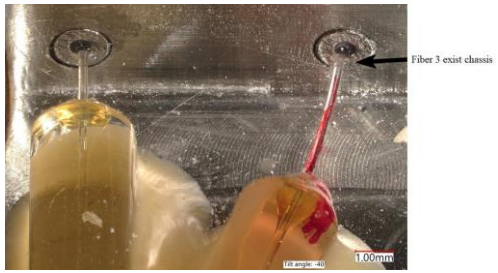
RF sideband phase noise measurement setup

2.3 OTHER MOPA COMPONENTS

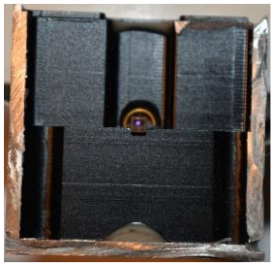
- **Components with previous spaceflight heritages**
  - Fused fiber couplers, monitor diodes, pressure sensor, getter, etc.
  - Low power isolator
    - Mostly qualified, used also in PA module
- **Components being qualified**
  - High power isolator
    - Custom magnetically-shielded isolator
      - DPA shows concerns with the isolator in TRL 4 LOM
      - Testing more compact isolator
  - Phase modulator
    - Using high power (>400mW) product
    - Photorefractive effect?
  - Low power switch, high power switch
    - DPA shows concerns with existing switches
    - Looking into other vendors
    - Requesting to remove the high power switch
  - In-line polarizer
    - Limited vendor with PM1060L fiber, needed because of the high power switch



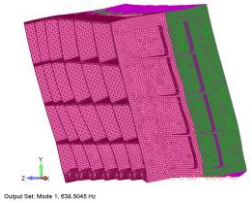
RF sideband phase noise of different amplifier models



Switch DPA example



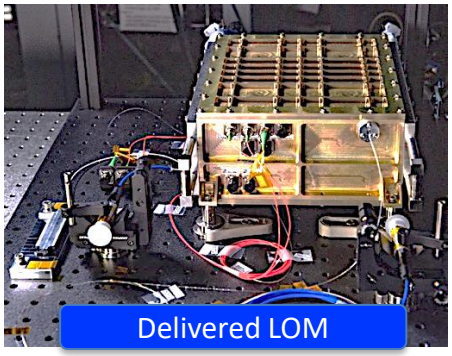
Isolator DPA example



LOM mechanical analysis

TRL4 PROTOTYPE AT CSEM

- **TRL-4 prototype laser was delivered to CSEM in May, 2021**
  - CSEM: Swiss private, non-profit, industrial research and development organization
  - Evaluates LISA laser candidates under ESA's contract
    - 3 main units: LOM, LEM based on COTS instrument, Low frequency RIN stabilization systems
    - Confirmed many of GSFC's pre-ship performance data
- **Issues identified**
  1. Large RF sideband phase noise
     - Missed in the pre-ship evaluation, small optical feedback?
  2. Loss of power event in Jun. 2022, after ~7000 hours of operation
     - Lasing caused by degraded seed power (due to photorefractive damage in phase modulator)
  - Hard lessons learned, corrective actions being taken (revisiting design and procedure)
  - The laser system is being sent back to GSFC for failure analysis and repair



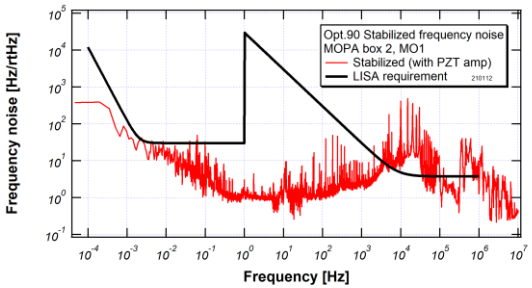
Delivered LOM



Delivered COTS-based LEM



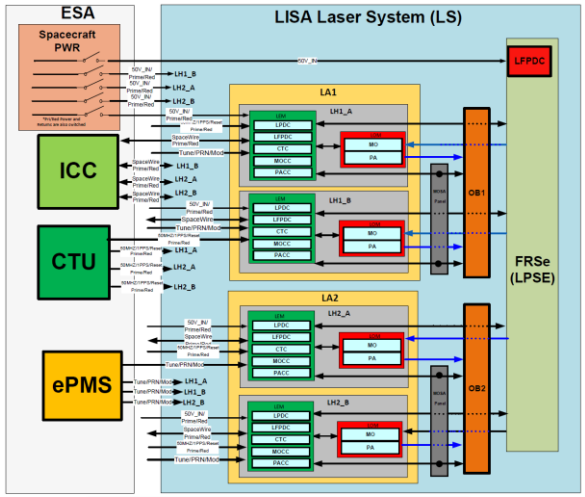
Delivered RIN stabilization systems



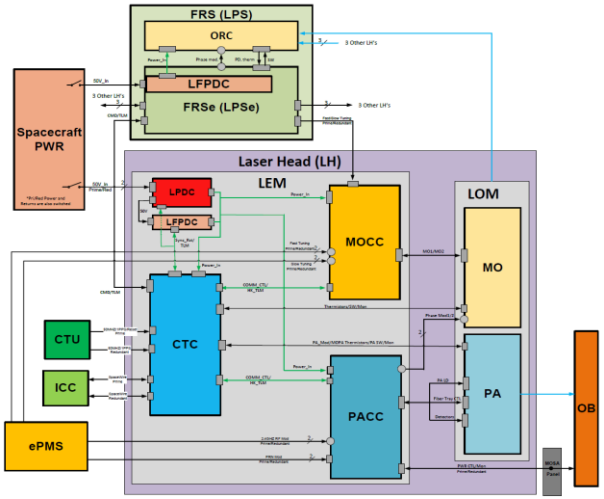
Pre-ship frequency noise performance

3. LASER ELECTRONICS MODULE

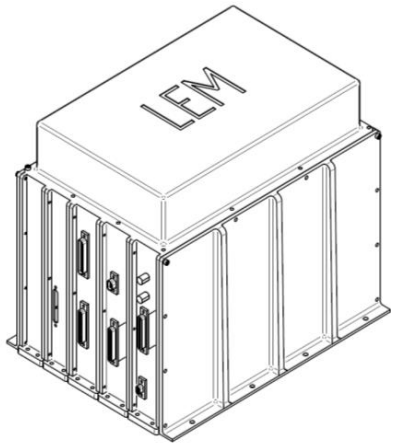
- **Led by GSFC electronics branch**
  - Multiple card design, Chassis design partly taken from previous missions
    - Power Distribution Cards (LPDC, LFPDC) : Convert 50V to other required DC voltages.
    - CTC (Command and Telemetry Card) : FPGA to handle other cards, TC/TM, housekeeping, etc.
    - MOCC (MO Controller Card) : Controls MOs
    - PACC (PA Controller Card) : Controls PAs, handles modulation signals
  - TRL5 version by end of this year, TRL6 version by 2023 summer
- **Current activities**
  - Passed TRL 5 peer review. Finalizing circuit schematics (for TRL5), parts procurement, simulations, etc.



LEM diagram at LS level



LEM system diagram



LEM chassis design

4. FREQUENCY REFERENCE SYSTEM

- **FRS with flight heritage**
  - Use improved version of GRACE-FO FRS
  - Developed by Ball Aerospace with JPL
  - Ball conducted improvement research on the GFO cavity with support from the LISA study office

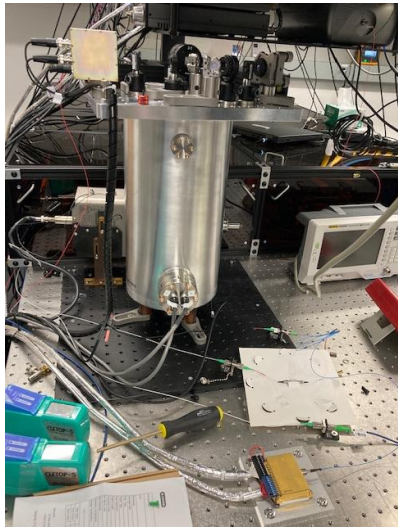
- **FRS procurement status**
  - Proposal from Ball was submitted on March 18, 2022.
  - Contract is currently being negotiated between Government and Ball
  - There have been multiple discussions regarding the technical proposal (related to LPS-E & FPGA).



Grace Follow-on cavity

- **FRS optics : optical reference cavity (ORC)**
  - Will use improved input optics design
  - Another change required: couple all 4 LHs into one cavity
  - GSE cavities
    - Stable Laser Systems: LISA like cavity. Working with µNPRO
    - Menlo Systems: Higher finesse, golden reference : Moving to SLAC.

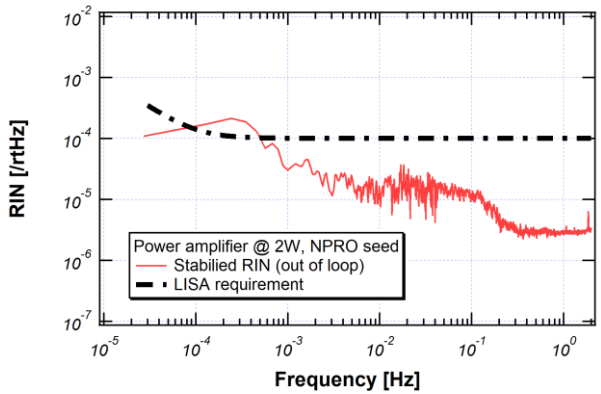
- **FRS electronics (FRS-E)**
  - Ball will ruggedize COTS electronics design and the FPGA software for TRL5 and 6
  - Power card will be provided by GSFC: common power card to LEM



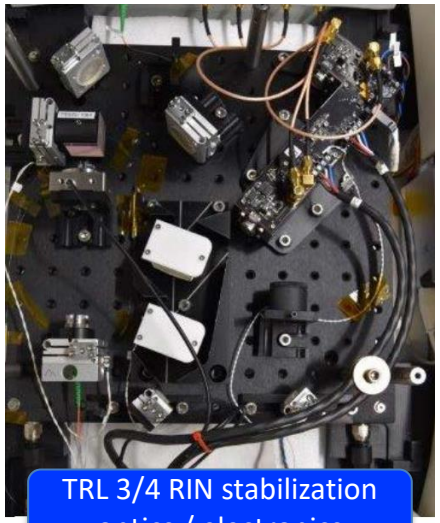
SLS GSE cavity and µNPRO locked to it

5. POWER MONITOR DETECTOR

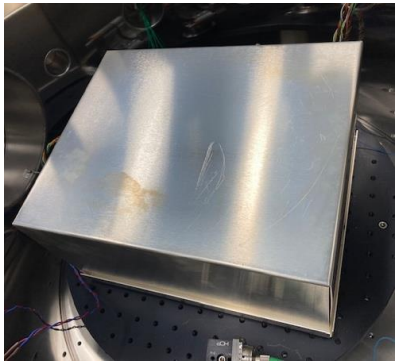
- **PMON on the LISA Optical Bench (OB) now part of laser deliverable**
  - ~10% of light picked off right before test mass
  - Used for stabilization of laser's low-frequency relative intensity noise (RIN)
  - Providing 2 photodetectors per OB
- **Two ~TRL 3/4 systems built**
  - One of them sent to CSEM : Used TEC-stabilized photodiode in air
- **Current TRL6 PMON activities**
  - Defining requirements & specifications, meeting with multiple vendors
  - Setting up device test bench & RIN performance test bench in vacuum tank
    - Building mock-up Zerodur OB



TRL ~3/4 RIN stabilization result



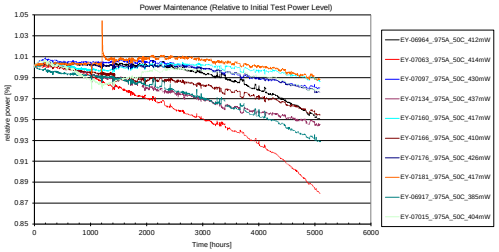
TRL 3/4 RIN stabilization optics / electronics



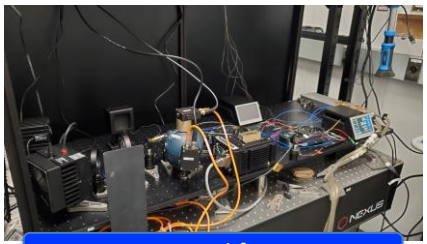
Thermal shield for the optical bench in vacuum

6. RELIABILITY

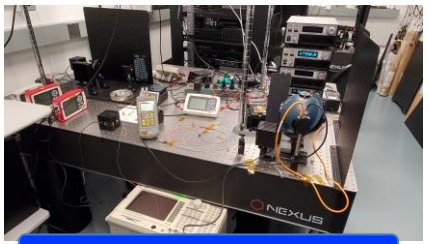
- **Performing analysis and testing at the component level**
  - Functional performance testing
  - Environmental testing (radiation, vibration, temperature cycle)
  - Magnetic field testing, Destructive Physical Analysis (DPA)
  - Life aging tests (especially for high power components)
- **Long-term life aging tests of pump diodes**
  - MO LD pump
    - Chip-on-Submount (CoS) level : Completed 5000h x 2, high stress level @ Eagleyard
    - Pump submount level: Low-Medium Stress Long-Term Life-Test started. Completed ~500h.
  - PA LD Pump
    - Previously tested for other mission. Started new tests for LISA. Also being done by ESA.
- **Upcoming activities**
  - Package (μNPRO) and LOM level life aging, more component level testing (phase modulator, high power switch), long-term non-operating condition tests, etc.



MO LD 975mA, 50C, 5000-hour test


PA component lifetest setup


MO (pump) lifetest setup


Component test station

7. DEVELOPMENT SCHEDULE

- **Schedule up to TRL 6, prior to flight model (FM)**
  - TRL6 LOM is on target to be delivered early summer 2023.
    - First EMQ LOM to be build by the end of this year
  - LEM development faced some contractual glitches initially, now catching up by direct management by GSFC electronics group
    - TRL6 LEM may not be ready if ESA MAR (Mission Adoption Review) to begin earlier than 10/2023.
  - TRL6 FRS delivery schedule may slip depending on when contract will be awarded.
    - FRS Cavity #1 – 10/23
    - FRS Cavity #2 – 3/24
    - FRS-E – 6/24

	FY22										FY23												FY24											
Date / Systems	12/21	01/22	02/22	03/22	04/22	05/22	06/22	07/22	08/22	09/22	10/22	11/22	12/22	01/23	02/23	03/23	04/23	05/23	06/23	07/23	08/23	09/23	10/23	11/23	12/23	01/24	02/24	03/24	04/24	05/24	06/24	07/24	08/24	09/24
LOM											TRL6 LOM1 Build & Env. Tests					TRL6 LOM2		TRL6 LOM3		TRL6 LOM4		TRL6 LOM5		TRL6 LOM6										
LEM	Start								TRL5 PDR			TRL5 LEM	Test TRL5 LEM with TRL6 LOM					TRL6 CDR			TRL6 LEM 1	TRL6 LEM 2	Envir Tests			Deliver to ESA								
FRS		Draft RFP	Actual RFP		Proposal Eval/Negotiate		Cnt Award								TRL4 LPS-E							TRL5 LPS-E	TRL6 C1					TRL6 C2			TRL6 LPS-E			
ESA Timeline															Laser TRA					ESA Adoption Review							SPC Adopt Decision						

Schedule to deliver TRL6 LH + FRS

8. SUMMARY

- **On-going laser development activities are designed to meet the requirements per ESA requirement**
  - Form, FIT and functionalities demonstration for packaged modules and systems by mid-2024
  - Continued TRL6 laser development and made key advancements to improve performance and reliability
  - Lessons learned from TRL 4 LOM will be fully incorporated into the TRL6 LOM/LEM designs.

- **Performing performance and environmental Tests**
  - Taking special cares for some performance areas such as RF sideband phase noise
  - Demonstrate pre- and post- environmental test performance as part of TRL6 maturation – planned for late 2023.

- **Laser reliability**
  - Key for the success of LISA : need 10~16 years lifetime. Unusual as a space laser.
  - Monitor aging tests performance of components, subsystems and system
  - On-going reliability analyses based on aging test data to demonstrate lifetime.

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