PERFORMANCE TESTING OF TRL4-6 LISA LASER SYSTEM

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for the LOM team, LEM team, PMON team, and FRS team

Special thanks to PMS team

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15th International LISA Symposium

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      - Main oscillator (MO) + Power amplifier (PA)
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  - TRL5 LEM + TRL6 MO + Representative PMS
- **4. Summary**

Jul. 10 (Wed) 11:30am at Main Hall

Advancement of the Laser System for the LISA Mission

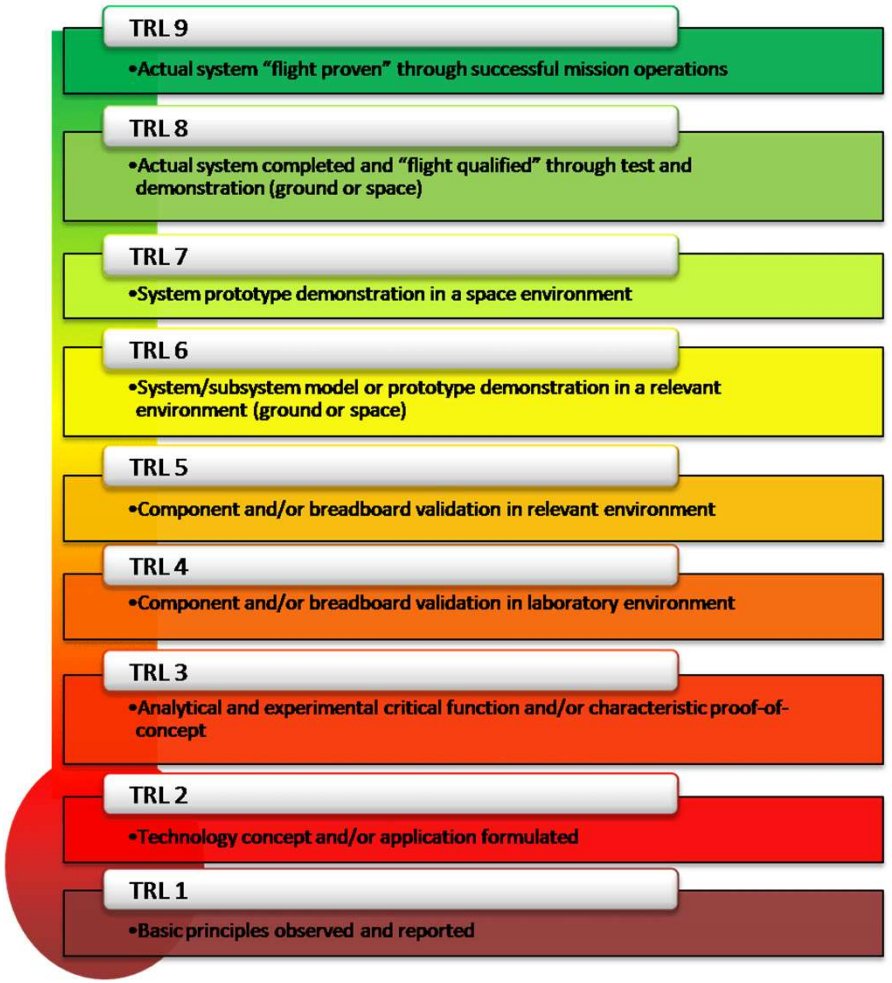
Plenary talk by Anthony Yu (NASA/GSFC)

1. INTRODUCTION

1. INTRODUCTION

- **Technology Readiness Level (TRL)**
  - A measure to assess the maturity level of a particular technology

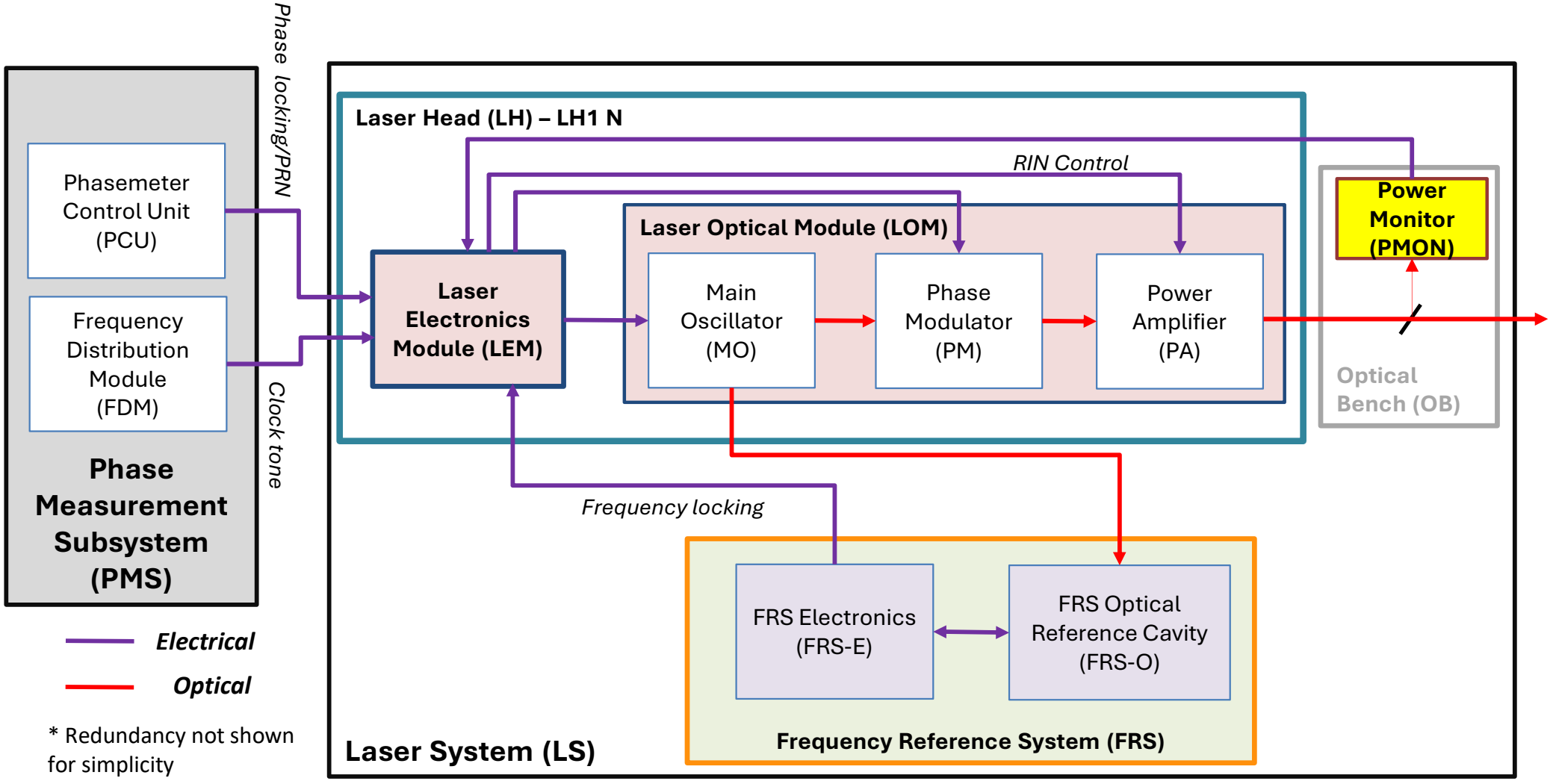
- **NASA LISA laser TRLs**
  - TRL4
    - Breadboard/component in lab environment
  - TRL5
    - Breadboard/component in relevant environment
  - TRL6
    - Prototype demonstration in relevant environment
  - TRL9
    - Flight proven unit



https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

All NASA LISA LS subsystems are at TRL 5 or TRL6 as of Jun. 2024.

LASER SYSTEM (LS)

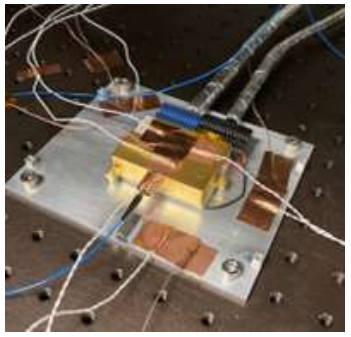


Performance testing between LS subsystems is critical for mission success.

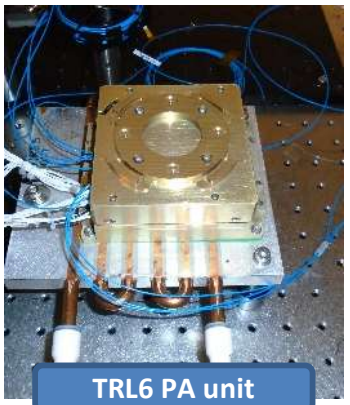
2. TRL OF LASER SYSTEM (LS) COMPONENTS

2.1 LASER HEAD (LH)

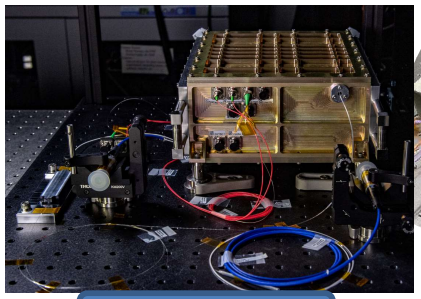
- **Laser optical module (LOM)**
  - Main Oscillator (MO)
    - Working with AVO Photonics
    - µNPRO : reached TRL6 in 2023*
    - Next generation (gen-3 EM/TRL6) rollout this summer
  - Power Amplifier (PA)
    - Working with Fibertek
    - Reached TRL6 in 2023*
    - Next generation (ETU, different form factor) being built
  - LOM box (includes phase modulator, switch etc.)
    - TRL4 version sent to CSEM for evaluation
    - TRL6 version built*
      - Vibration test this week. TVAC test next month.
- **Laser electronics module (LEM)**
  - TRL5 version built, under testing*
  - TRL6 version (ETU) being designed.



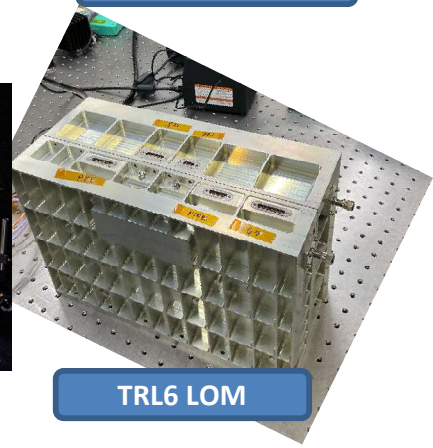
µNPRO thermal cycle tests for TRL6



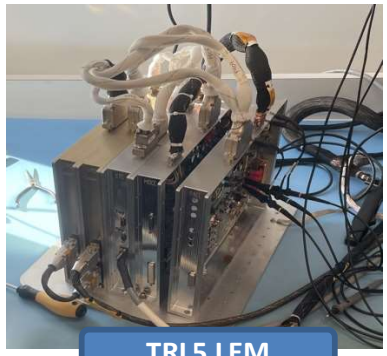
TRL6 PA unit



TRL4 LOM



TRL6 LOM



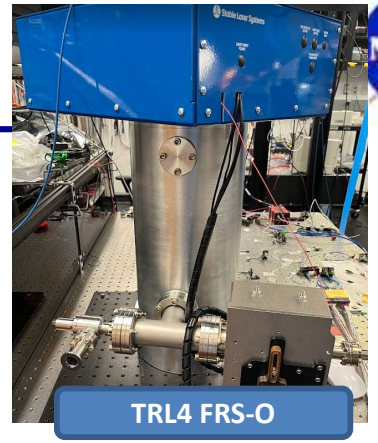
TRL5 LEM

* : Components reported here

LH is being qualified for TRL6.

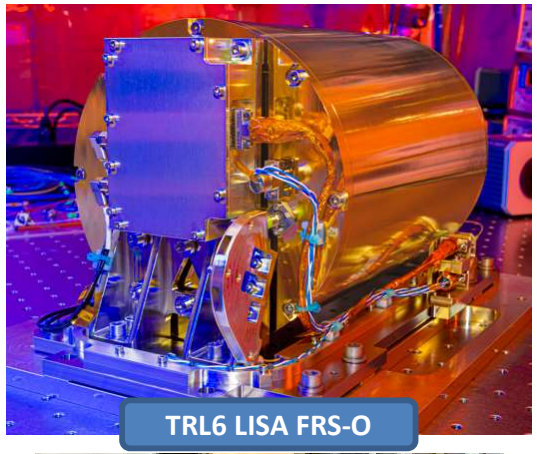
2.2 FREQUENCY REFERENCE SYSTEM (FRS)

- **TRL4 (GSE) FRS**
  - Worked with Stable Laser Systems
  - Cavity with same geometry, material, and finesse
  - COTS FPGA electronics*
    - Basis for TRL6 FRS-E



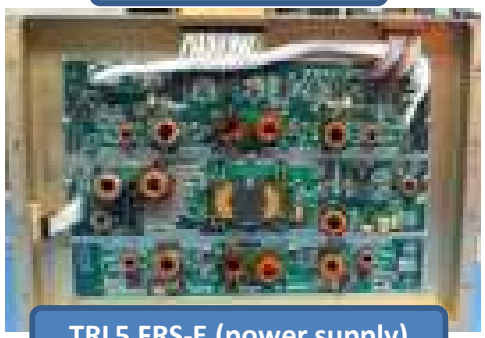
TRL4 FRS-O

- **FRS-O**
  - Based on the TRL9 version flown on GRACE-FO
  - Some parts modified for further improvement
  - TRL6 version to be delivered next month



TRL6 LISA FRS-O

- **FRS-E**
  - New addition to the GRACE-FO cavity
  - TRL5 version to be delivered next month
  - TRL6 version under development

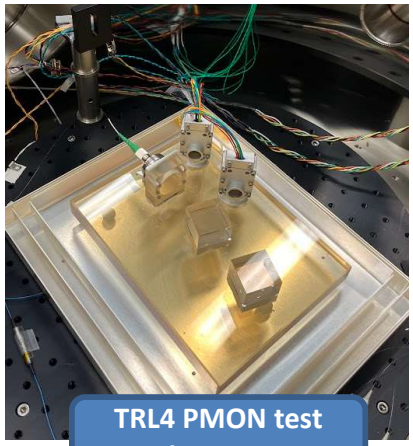


TRL5 FRS-E (power supply)

See poster #P142 **Development of Frequency Reference System for LISA Laser** by Jennifer Lee *et al.* for details

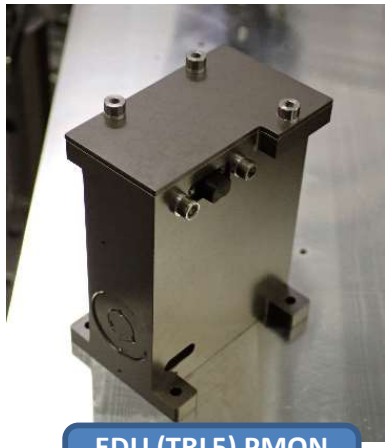
2.3 POWER MONITOR (PMON)

- **TRL4 versions**
  - GSE setup in ambient air
    - Used in performance demonstration at CSEM
  - Test under vacuum
    - Used to demonstrate performance at GSFC



TRL4 PMON test under vacuum

- **EDU (TRL5) version***
  - Built by AVO Photonics
  - 4 units delivered to GSFC for evaluation
  - 2 photodiodes in 1 unit
  - Including a lens, a beamsplitter, a mirror, baffles, and TIAs.



EDU (TRL5) PMON assembly

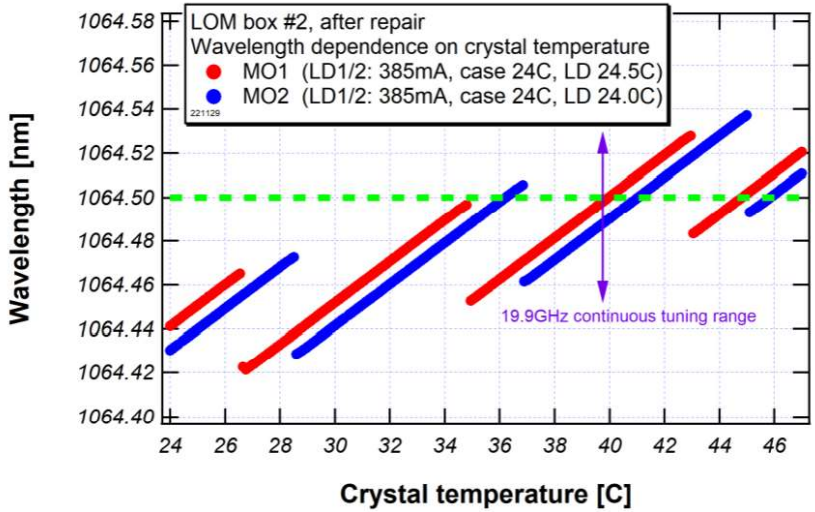
- **ETU (TRL6) version**
  - Planned delivery next fall
  - Will be compatible with the updated flexure mount provided by the OB
  - Full vacuum compatibility
  - Will meet magnetic requirement

See poster P138 **Review and performance testing of the optical power monitor (PMON)** by Hua Jiao *et al.* for details

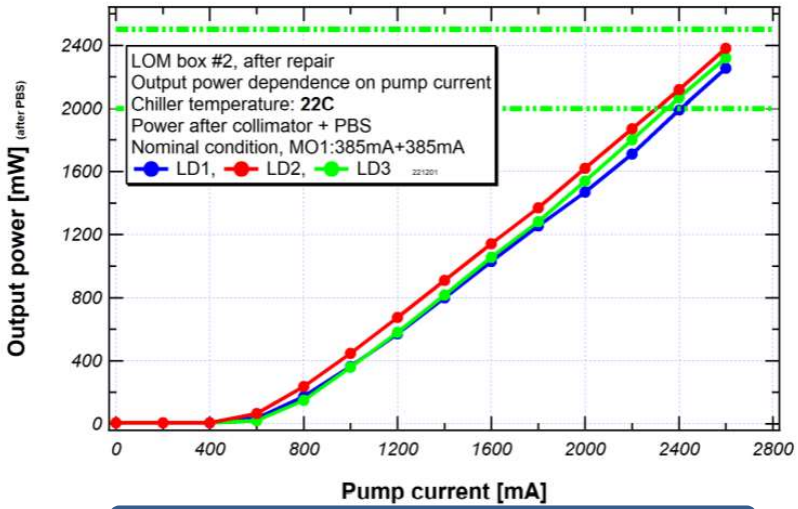
3. SYSTEM LEVEL TESTS

LASER HEAD (LH) ONLY – TRL4 LOM

- **TRL4 LOM testing**
  - Experienced failure after ~4000 hours
    - Identified the cause of the failure by analyses, and replaced the problematic component
    - Implemented this design change to TRL6 LOM
  - Loaded with TRL6 MO, more TRL6-like PA module during repair (Jan. 2023)
    - Working without failure or degradation since then at CSEM
    - New Z-cut modulators are under life test over 5000 hours without degradation



Tuning property of TRL6 MO in TRL4 LOM

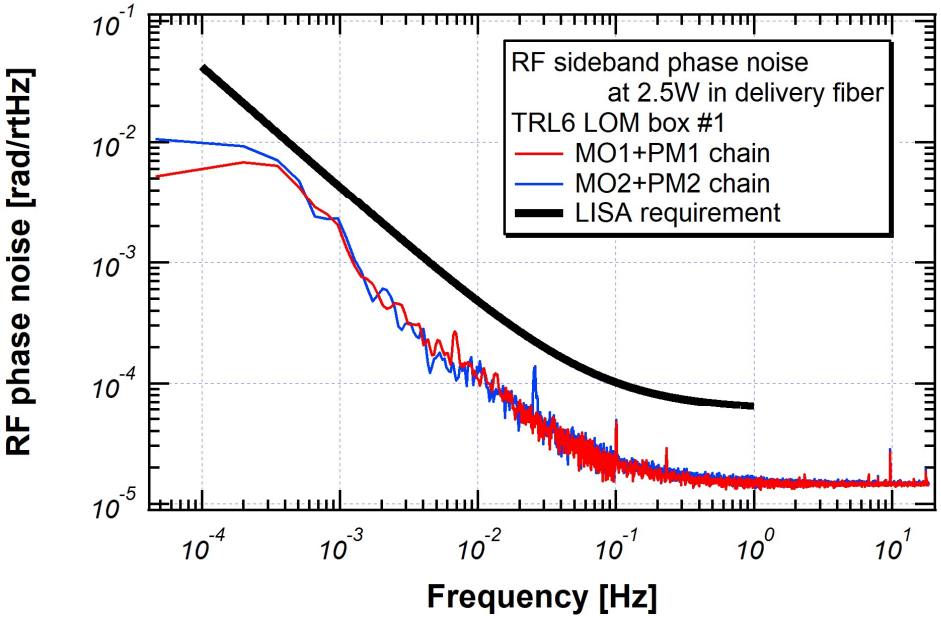


Output power of TRL4 LOM

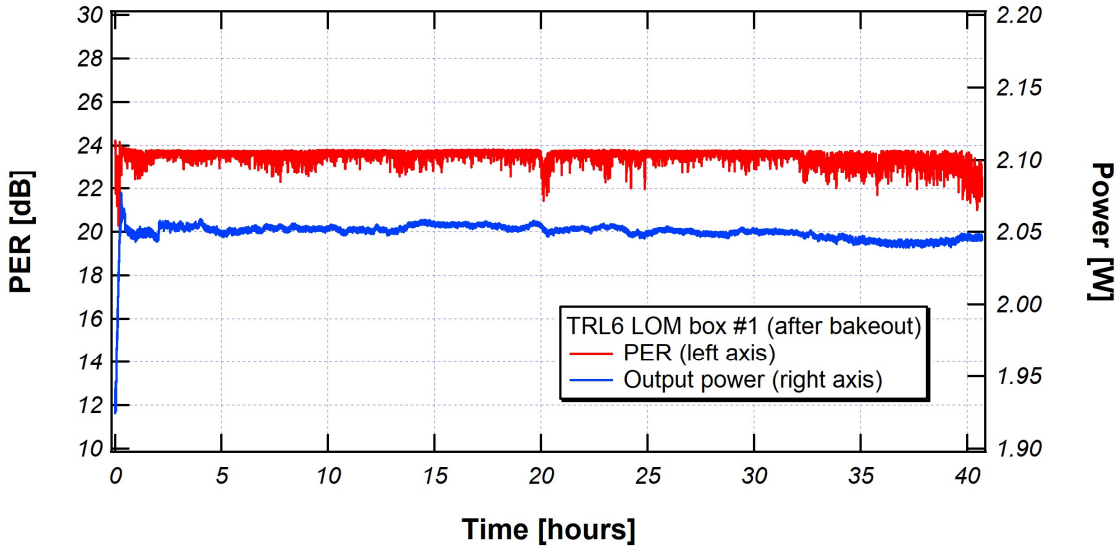
Lessons learned from TRL4 (failure) were reflected to TRL6 LH designs and test procedures. TRL4 laser is working over a year at 2W after the repair.

LASER HEAD (LH) ONLY – TRL6 LOM

- **Some performance figures of TRL6 LOM**



RF modulation phase noise at 2.5W



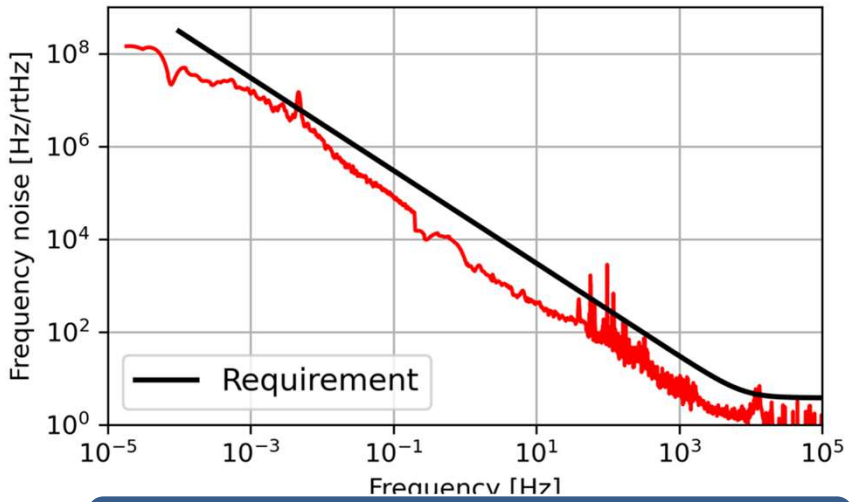
Polarization extinction ratio (PER) over time

TRL6 LOM is meeting all challenging requirements.

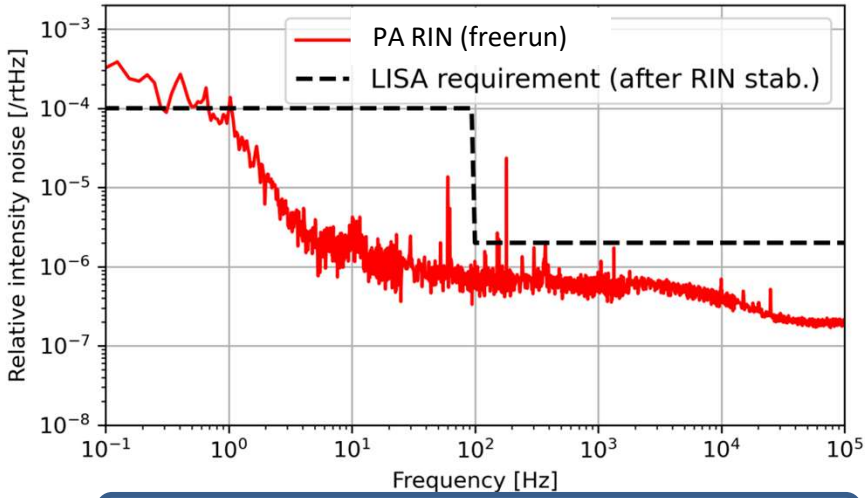
P125 RF differential phase noise measurements of the LISA TRL-6 laser
by Xiaozhen Xu *et al.*
P121 Modeling the thermal sources of RF phase noise for the LISA laser transmitter
by Jennifer Campbell *et al.*

LASER HEAD (LH) ONLY – TRL5 LEM + TRL4 LOM

- **Development of low noise laser drivers was the key.**
  - Based on space-compatible components
    - Ultra-low noise laser current driver selected from different architectures
  - Analog temperature controller on TRL5 LEM to maintain heritage from TRL4
    - Digital PID controller independently developed and tested
    - To be implemented into TRL6/ETU LEM



Frequency noise of TRL6 MO driven by TRL5 LEM (freerun)

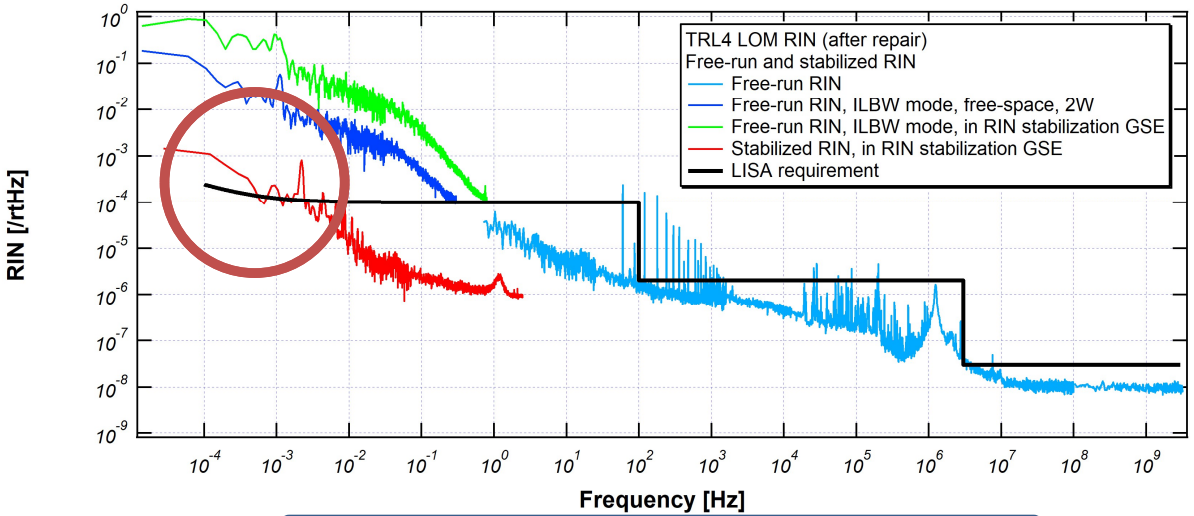


Relative intensity noise of TRL4 PA driven by TRL5 LEM (freerun)

Have credible circuit designs to meet low frequency/intensity noise requirements

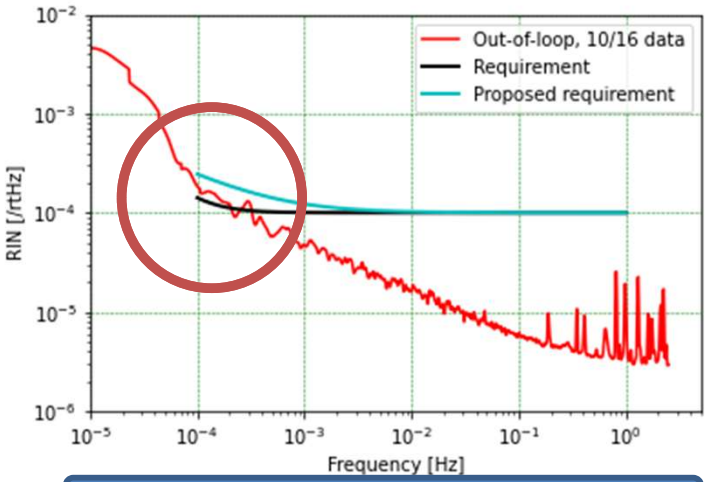
POWER MONITOR (PMON) + LH

- **TRL 4 LH + GSE PMON**
  - In air
  - Active temperature control
  - With PA, at 2W



TRL4 LOM + GSE PMON RIN over full frequency range

- **TRL4 PMON only test**
  - In vacuum
  - Passive temperature control
  - Zerodur bench
  - No PA, TRL6 MO only
    - To check PMON only performance

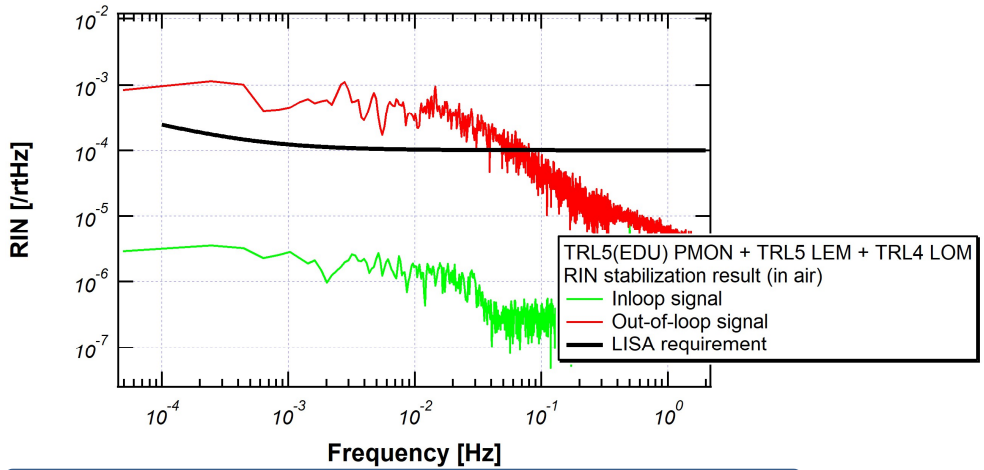


TRL6 MO + TRL4 PMON test at low frequency

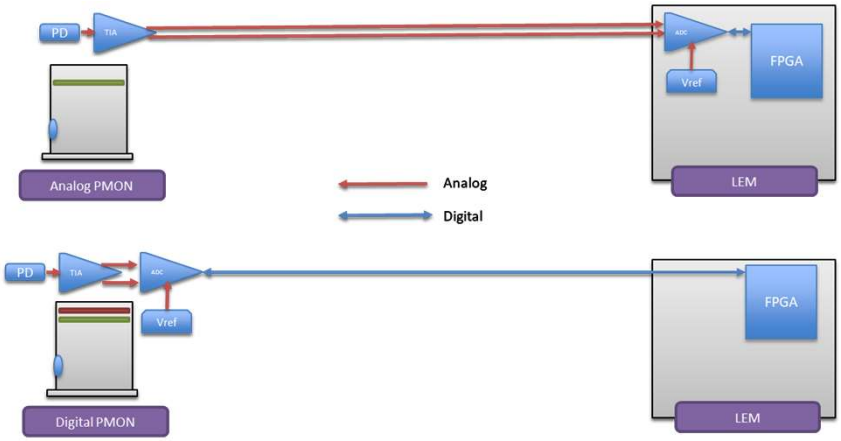
Meeting the RIN requirement at the lowest frequency has been a challenge. Negotiations have been made between ESA and NASA.

POWER MONITOR (PMON) + LH

- **TRL5 (EDU) PMON + TRL4 LOM + TRL5 LEM**
  - First system test
    - Interface works
    - RIN servo in LEM + FPGA logic works
  - In air
    - No temperature control/shield
  - Full analog electronics
    - Susceptible to temperature drift
    - 1/f or drift noise
      - Going for digital servo system
- **Potential issue in S/C**
  - Long analog cable
    - Is it possible to maintain ~10μV/√Hz@0.1mHz?
  - Digital PMON concept proposed (rejected by ESA)



First TRL5 PMON + LEM RIN stabilization result (in air)



Digital PMON concept proposed

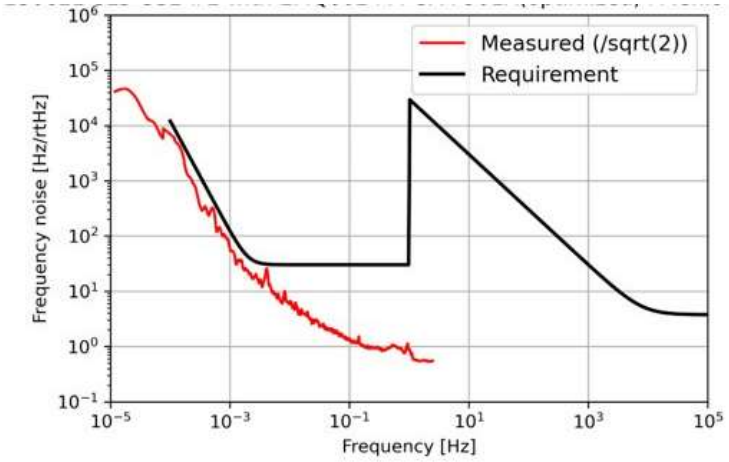
Performance will depend on PMON and harness environment. Verification of this requirement will be a major challenge.

FREQUENCY REFERENCE SYSTEM (FRS) + LH

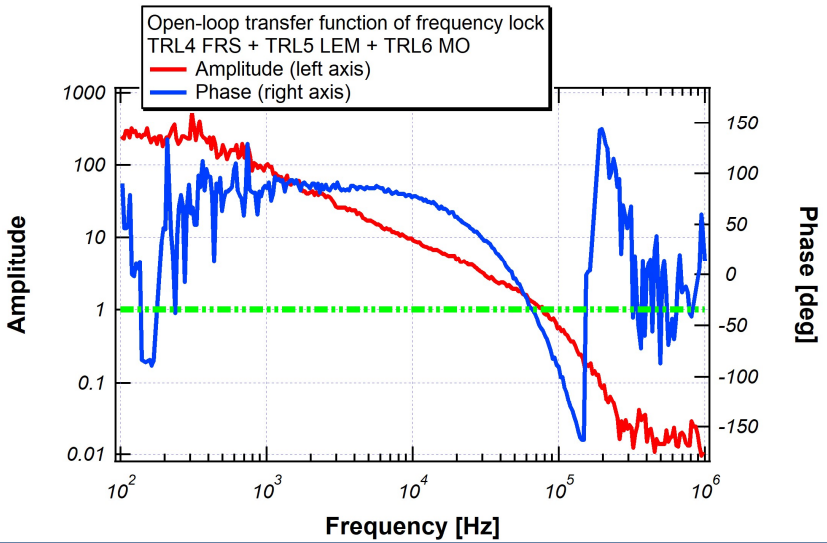
- **TRL4 LOM + TRL4 FRS**
  - Loaded with TRL6 µNPRO
  - Meeting frequency noise requirement

- **TRL4 LOM + TRL5 LEM + TRL4 FRS**
  - Loaded with TRL6 µNPRO
  - Testing analog interface of TRL5 LEM
  - Analog filter for PZT peak suppression
    - Achieved >80kHz unity gain frequency with >90deg phase margin

- **TRL6 MO + TRL6 FRS-O + TRL5 FRS-E**
  - To be tested in Aug. 2024



Frequency noise performance of TRL4 FRS + TRL6 MO

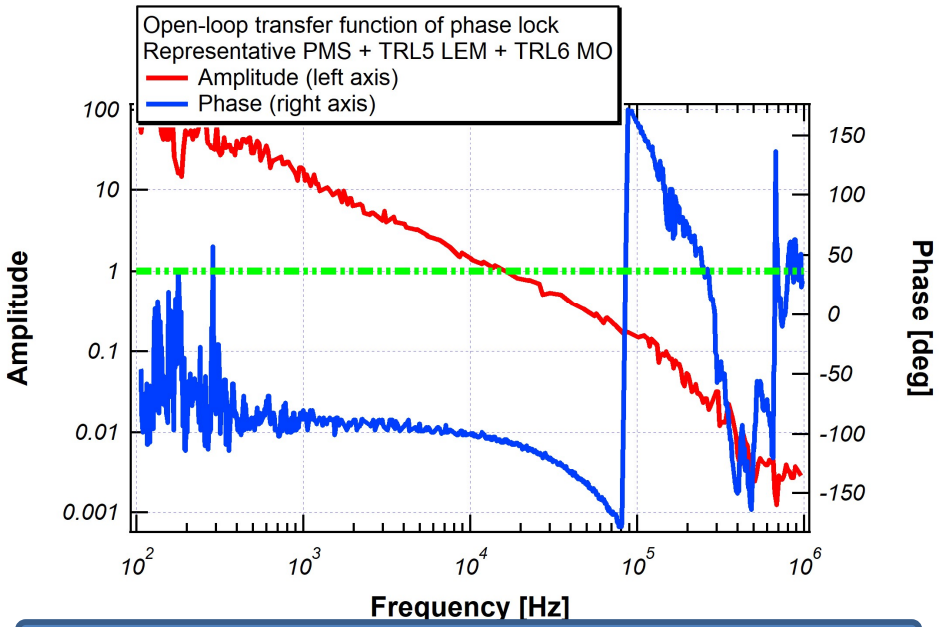


Open-loop transfer function of TRL6 MO + TRL5 LEM + TRL4 FRS

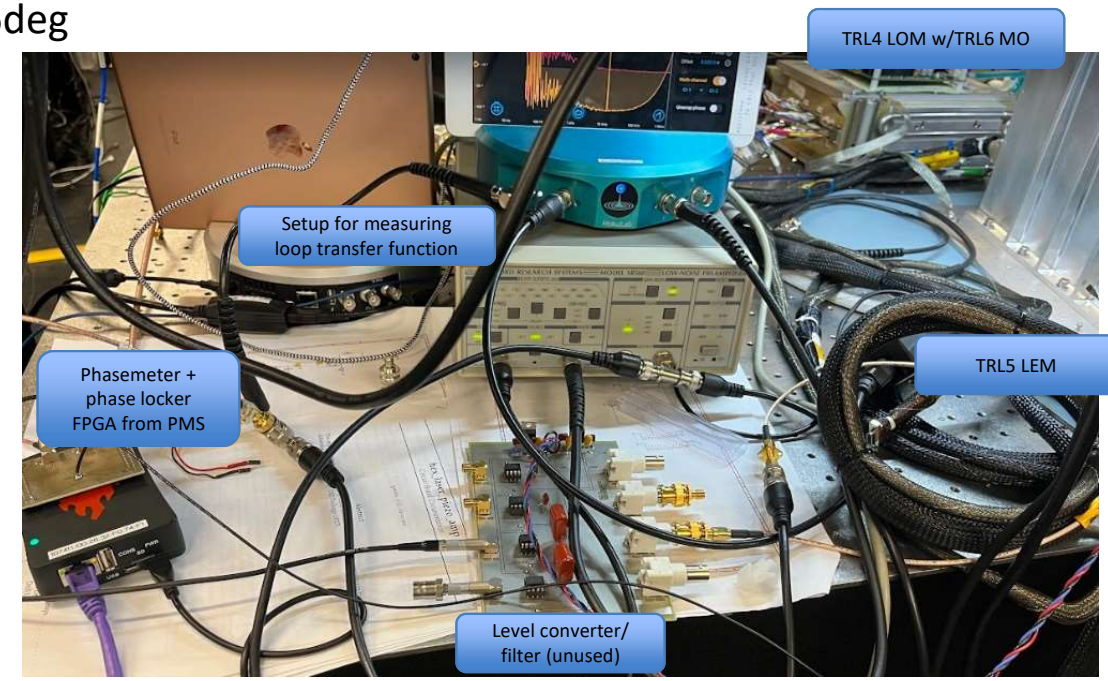
TRL6 µNPRO + cavity with same parameters + TRL4 FPGA controller can meet the LISA's frequency noise requirement, 30Hz/√Hz.

PMS + LH

- **Representative PMS + TRL5 LEM + TRL6 MO**
  - Interface test done with PMS team at NASA/GSFC on Feb. 2024
  - COTS FPGA board loaded with the same PM algorithm
  - Successful phase lock demonstrated
    - Residual phase noise meeting performance (in-loop evaluation)
    - Unity gain: 16.4kHz, phase margin: 76deg



Open-loop transfer function of TRL6 MO + TRL5 LEM + PMS



PMS – LH interface (phase-locking) test setup

Current LH design is compatible with the latest PMS logic to meet the phase-lock performance requirement.

4. SUMMARY

SUMMARY AND OUTLOOK

- **Testing LS components by combining them**
  - All results look promising so far
    - Key performance requirements have been met with maturing hardware
  - Identified challenges for TRL6+

- **Expected changes in TRL6/ETU LH**
  - Implementing new concepts for further improvement and de-risking
    - LH : Digital controllers
    - PMON/RIN control : Digital servo, digital modulation signal injection
    - PMS-LH, FRS-LH frequency tuning interfaces: Digital connection
  - Will perform full testing with TRL6/LH

- **Will keep performing system-level tests with high TRL components as possible**
  - Will repeat interface testing
  - Will perform tests in thermal vacuum chamber
  - Laser system (LS) test required before delivery to ESA
    - 4 LH + 2 PMON + 1 FRS
  - Test environment being prepared
  - EMI/EMC tests, thermal tests, and life aging tests planned (unit level or system level)