Iodine-Stabilized Laser Modules for LISA Ground Test Campaigns

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[1] *LTE* [2] *EXAIL (Kylia)*

Consortium LISA-France :
APC, ARTEMIS, CEA, CPPM, Institut FRESNEL, LAM, LTE, CNES

- ❑ Laser Requirement for Lisa Mission Grounds Tests
- ❑ A Compact-Transportable Iodine Stabilized Laser Setup
- ❑ Laser Characterization Using LTE's Frequency Chain
- ❑ Interferometry Test under Vacuum at LAM (Marseille) (July – September 2023)

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  - On each satellite : 2 lasers @ ~ 1064.49 nm (+ 2 backups)
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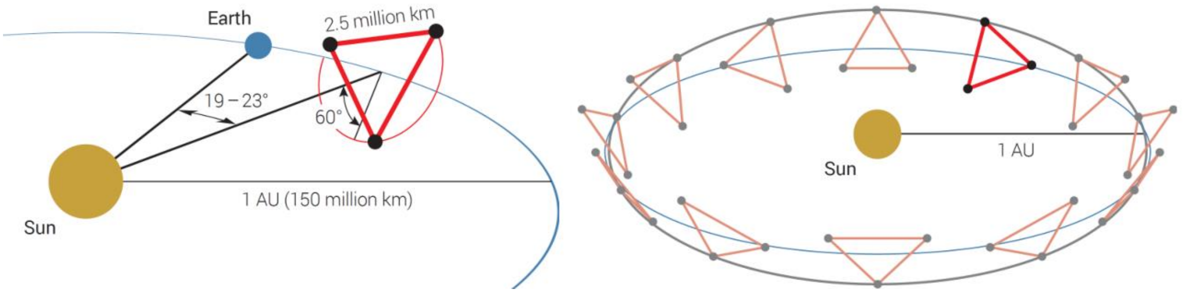
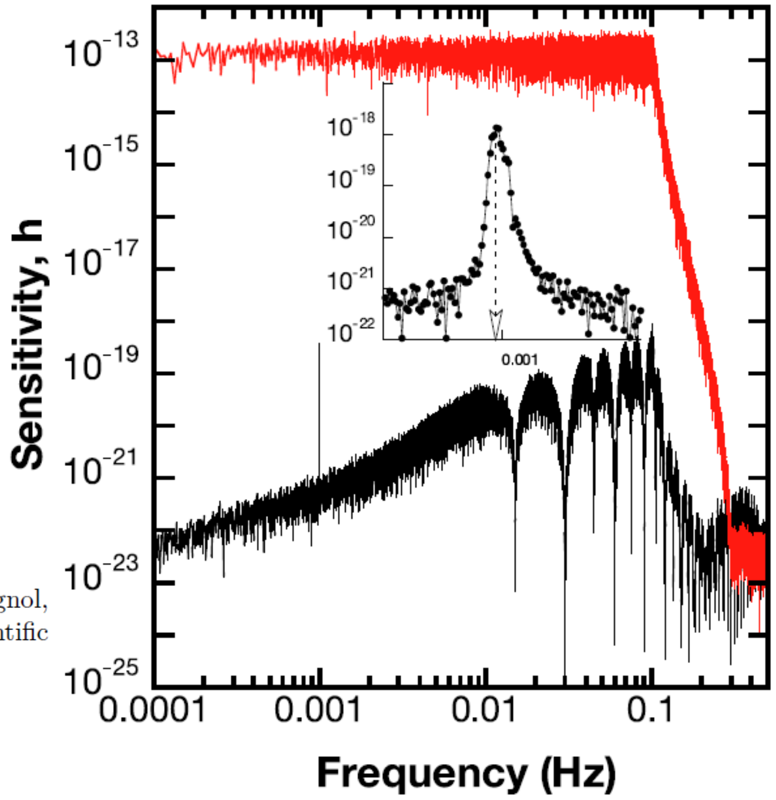


Relative frequency fluctuation between 1s and 1000s:

$$\boxed{\frac{\delta\nu}{\nu} \leq \frac{hL}{2\Delta L} \approx 5 \times 10^{-20}}$$

Major Source of instrumental noises :
Frequency noise coming from the laser

TDI →



Thanks to TDI, the noise is rejected to 10^{-13}

$$\boxed{\boldsymbol{\frac{\delta\nu}{\nu} \leq 10^{-13}}}$$

$$\boxed{S_{laser}^{1/2} \sim 30\frac{Hz}{\sqrt{Hz}}\sqrt{1+\left(\frac{3mHz}{f}\right)^4}}$$

Antoine Petiteau, Gérard Auger, Hubert Halloin, Olivier Jeannin, Eric Plagnol, Sophie Pireaux, Tania Regimbau, and Jean-Yves Vinet "LISACode : A scientific simulator of LISA, Phys. Rev. D" 77, 023002 – Published 17 January 2008

Lisa Requirements

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LISA FRANCE	CCTP POUR LES ACTIVITES DE TEST DU DEMONSTRATEUR D'INTERFEROMETRE ZERODUR « ZIFO » AU LAM – LABORATOIRE SYRTE Non sensible	Réf : LISA-PRO-SOW-0114-CNES Date : 26/07/2022 Edition : 1.0 Page : 7/9

1. OBJET DU DOCUMENT

Ce document constitue le Cahier des Clauses Techniques Particulières relatif à la participation du laboratoire SYRTE aux activités de test du démonstrateur interférométrique Zerodur dénommé « ZIFO » prévues pour être réalisées en utilisant les infrastructures de test sous vide du laboratoire LAM.

2. CONTEXTE

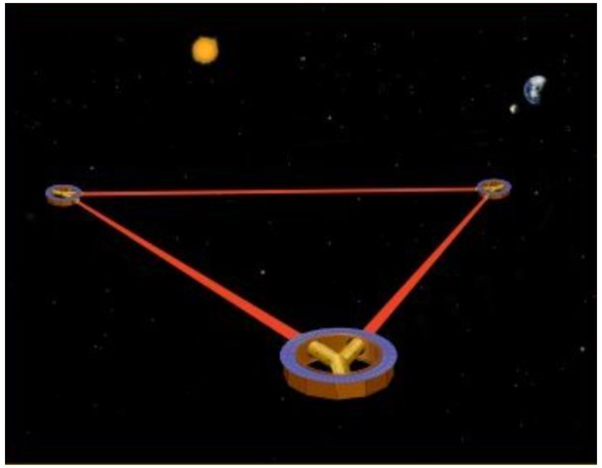
LISA est la mission L3 de l'ESA, pour l'observation des ondes gravitationnelles. Dans ce cadre, outre la participation scientifique, les principaux éléments de la contribution française sont les suivants :

1. Définition des tests de performance MOSA et réalisation des moyens de test optiques complexes associés (projet OTS du consortium)
2. Activités d'AIVT du système interférométrique (projet IDS du consortium)
3. Développement du DDPC incluant la simulation des données
4. Participation aux travaux relatifs au modèle de performance mission

La contribution française est assurée par la communauté LISA-France, avec la participation et la coordination du CNES, et la participation de nombreux laboratoires. L'organisation LISA-France et son rôle au sein du consortium est précisée dans le plan de management [DA01].

Les contributions relatives aux projets IDS et OTS nécessitent certains développements technologiques préparatoires. Parmi ces développements, la communauté LISA-France a lancé dès la phase A le développement d'un démonstrateur de banc optique Zerodur avec optiques adhérées. Ce développement technologique a notamment les objectifs suivants :

- Accroitre la connaissance des équipes en métrologie hétérodyne de haute précision
- Caractériser l'impact de l'environnement de test sur les précisions de mesure (température, vibrations, pression)
- Mesurer les performances de stabilité interne du banc dans la bande passante de LISA, en particulier [30 mHz, 1 Hz].



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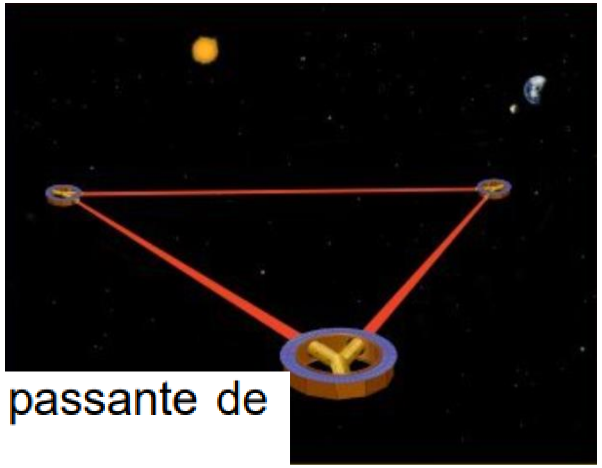

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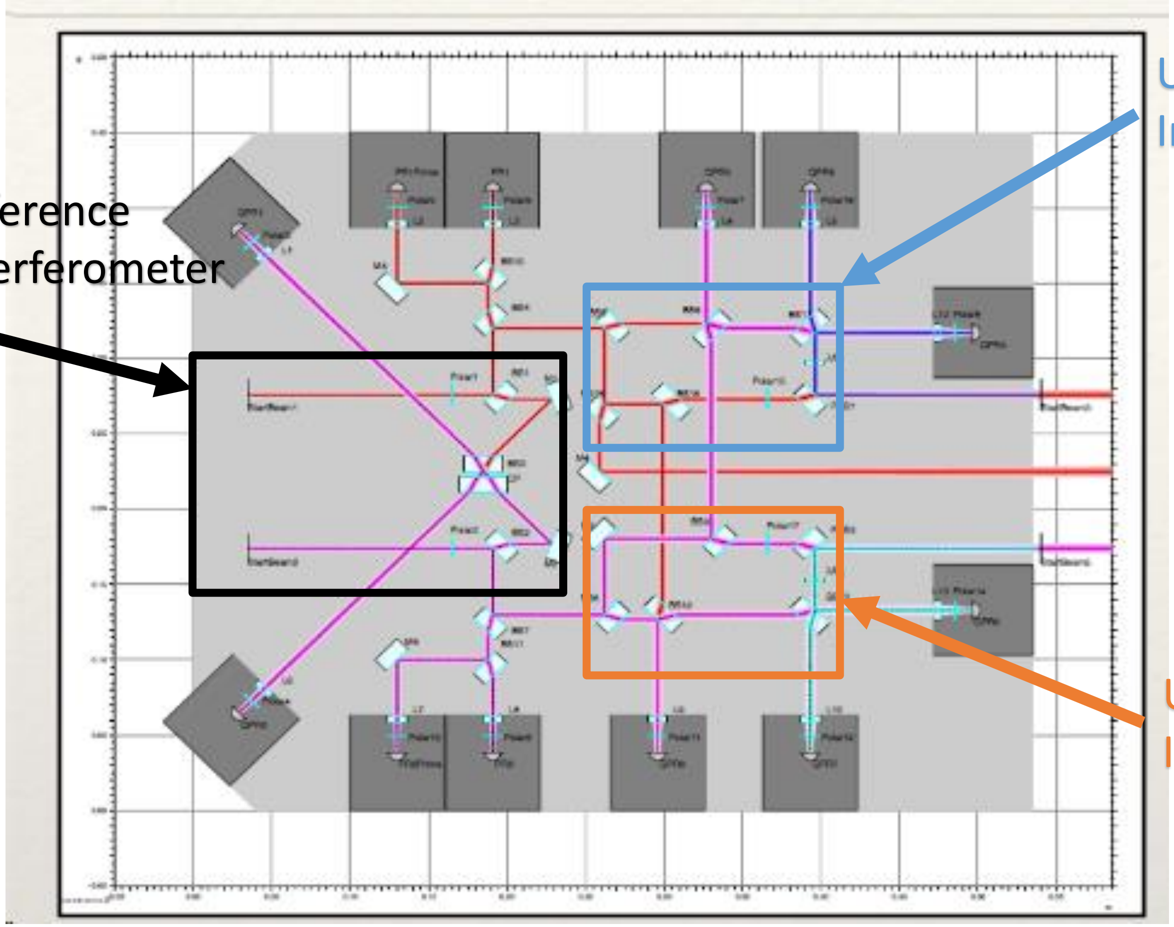
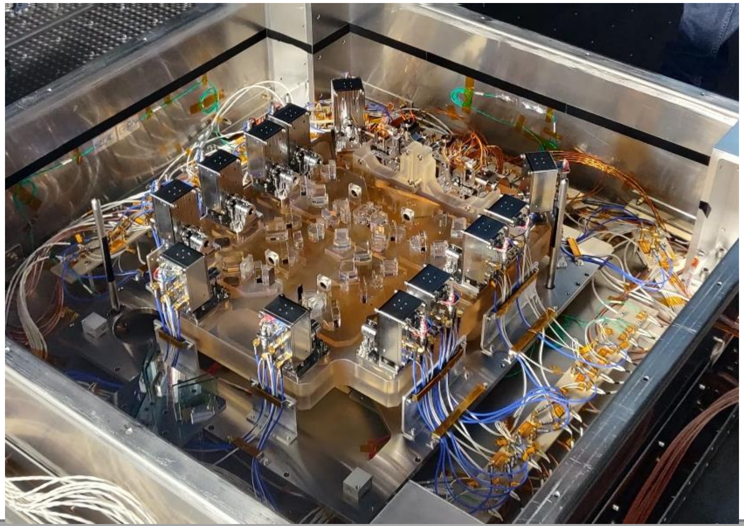
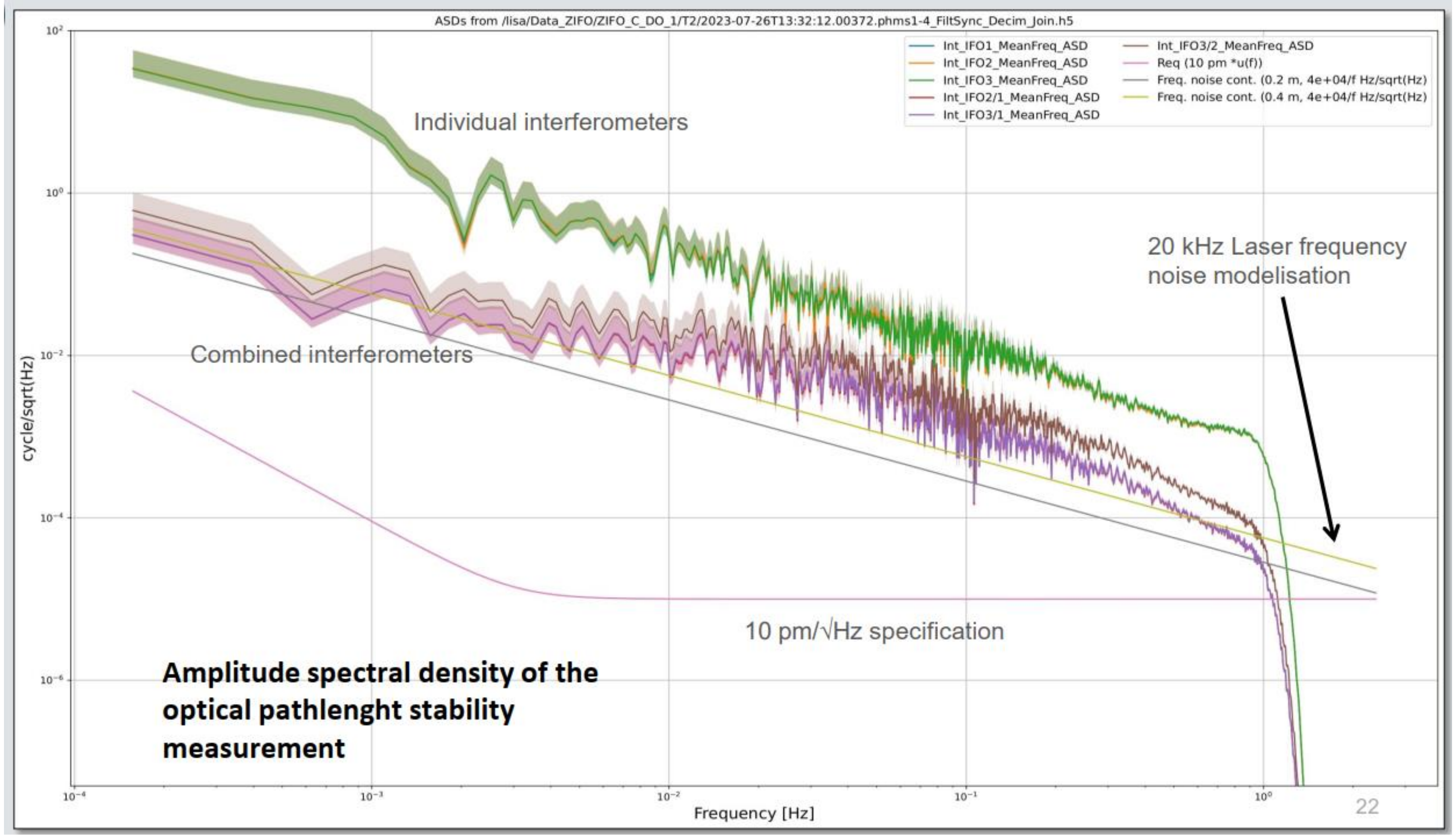
ZIFO: An heterodyne interferometry demonstrator



Some of the Main Objectives :

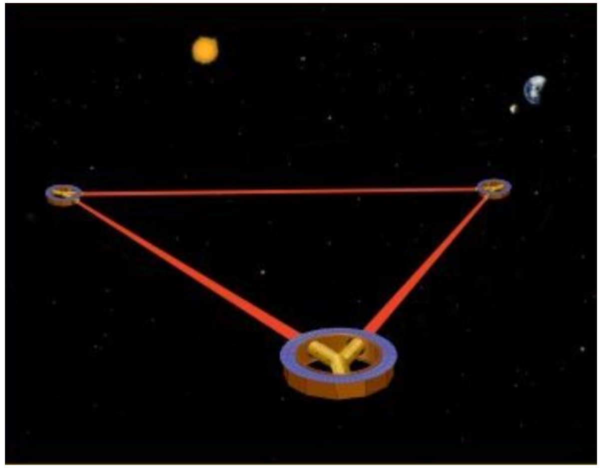
➢ Optical path length measurement with a noise of 10 pm/√Hz in the 0,1 mHz to 1 Hz frequency band





ASDs from /lisa/Data_ZIFO/ZIFO_C_DO_1/T2/2023-07-26T13:32:12.00372.phms1-4_FiltSync_Decim_Join.h5
Int_IFO1_MeanFreq_ASD
Int_IFO2_MeanFreq_ASD
Int_IFO3_MeanFreq_ASD
Int_IFO2/1_MeanFreq_ASD
Int_IFO3/1_MeanFreq_ASD
Int_IFO3/2_MeanFreq_ASD
Req (10 pm *u(f))
Freq. noise cont. (0.2 m, 4e+04/f Hz/sqrt(Hz)
Freq. noise cont. (0.4 m, 4e+04/f Hz/sqrt(Hz)
Individual interferometers
Combined interferometers
20 kHz Laser frequency noise modelisation
10 pm/√Hz specification
Amplitude spectral density of the optical pathlenght stability measurement
cycle/sqrt(Hz)
Frequency [Hz]
22

- Space large interferometer, based on 1064,49 nm Nd: YAG lasers.
  - On each satellite : 2 lasers @ ~ 1064.49 nm (+ 2 backups)
  - Emission laser 2 Watt. Reception ~ 500 pW.
- To reach the Lisa Mission requirement, the residual frequency noise should be 30 Hz/√Hz in the frequency band of interest
- Need 1 frequency reference embedded on each satellite.
- Nominal frequency reference for the LISA mission: ultrastable optical cavity.
- The back-up solution, stabilization on a hyperfine transition of Iodine @ 532.245 nm
- The ground-test operation of the LISA mission would be led in several laboratory all over France which is not suitable with the use of an ultrastable cavity.
- Based on the long development of iodine-based frequency reference, the LTE has provided a solution : **a compact transportable Nd:YAG Laser tandem phase lock on an iodine frequency reference**



Iodine cell

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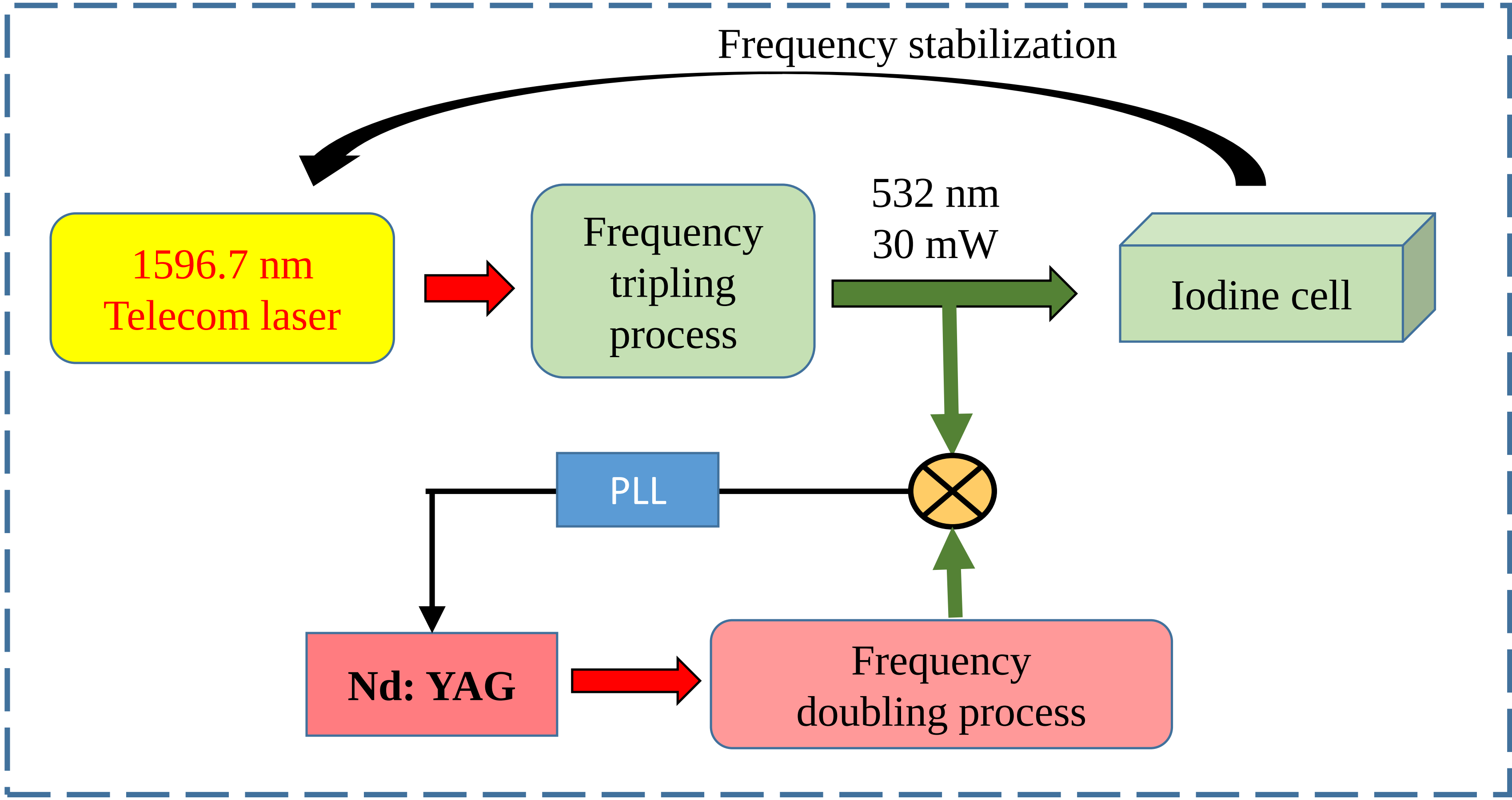
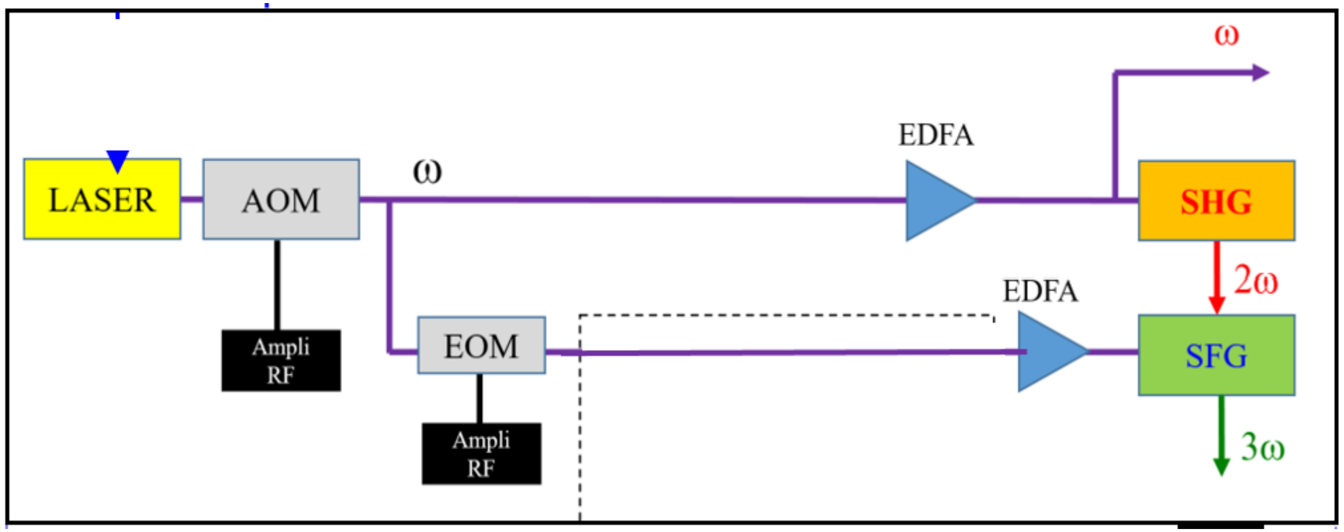
- The reference laser is a frequency tripled telecom fiber laser at 1596,73 nm, frequency stabilized against the a_1 component of the R 56 [32-0] $^{127}I_2$ line at 532.245 nm.

- The frequency gap between the IR and green ranges is bridged using a tandem of PPLN crystals :
  (SHG: w + w → 2w) and
  (SFG: w + 2w → 3w).



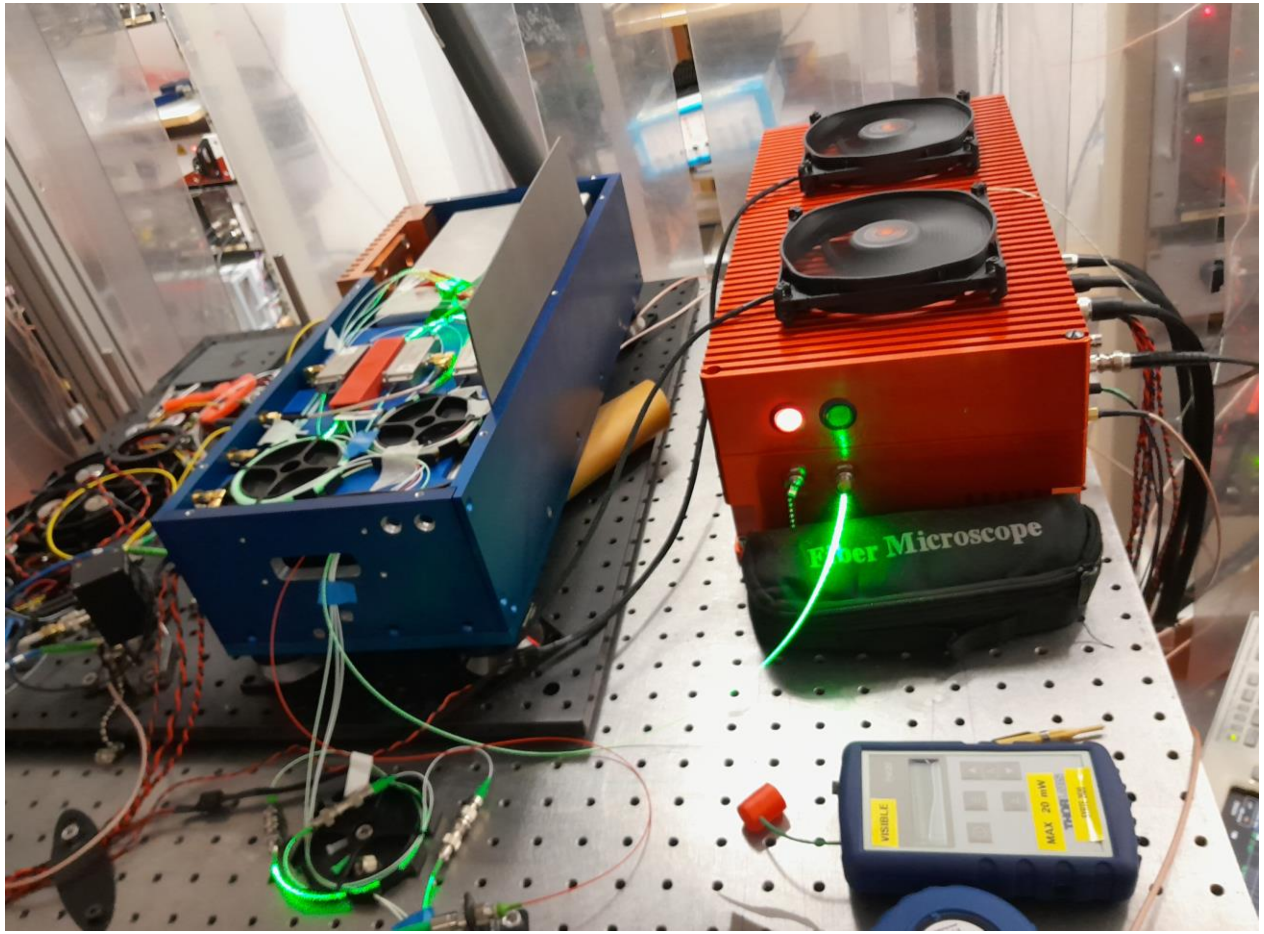


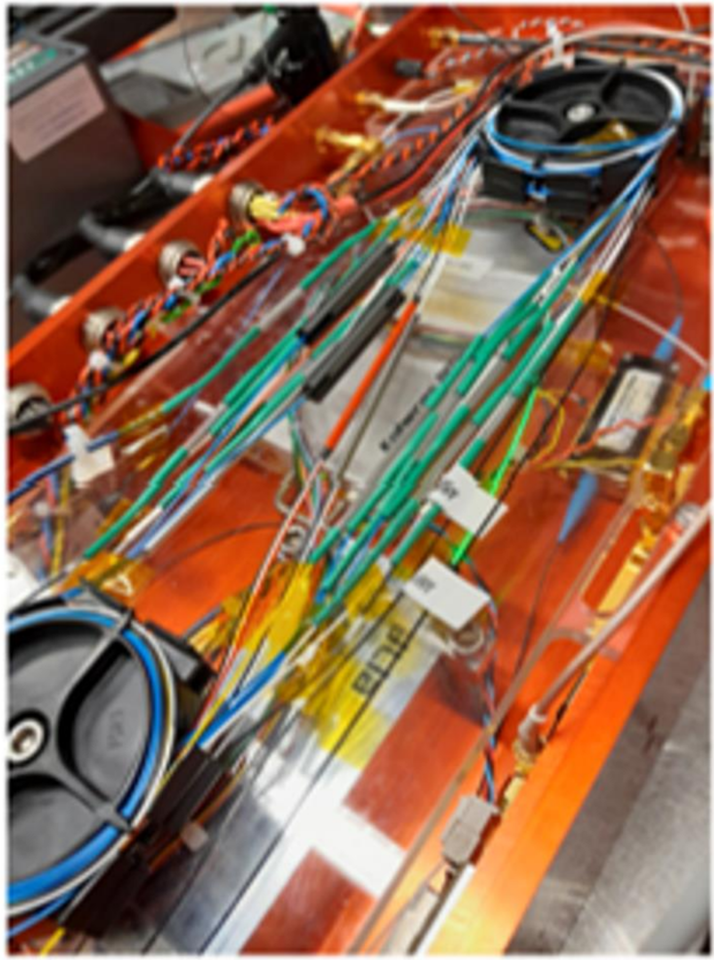
- Frequency modulation could be done with EOM for 3rd order derivative.
- Frequency lock is realized on the AOM and PZT of the Laser
- Fibered Erbium doped laser linewidth < 1kHz

SHG (w + w → 2w) LiNb03 PPLN-WG (NEL /Japon)
L= 34 mm, 10 x 10 µm²
η ~ 90 % W^{-1}
500 mW à 1596 nm, 220 mW @ 798 nm

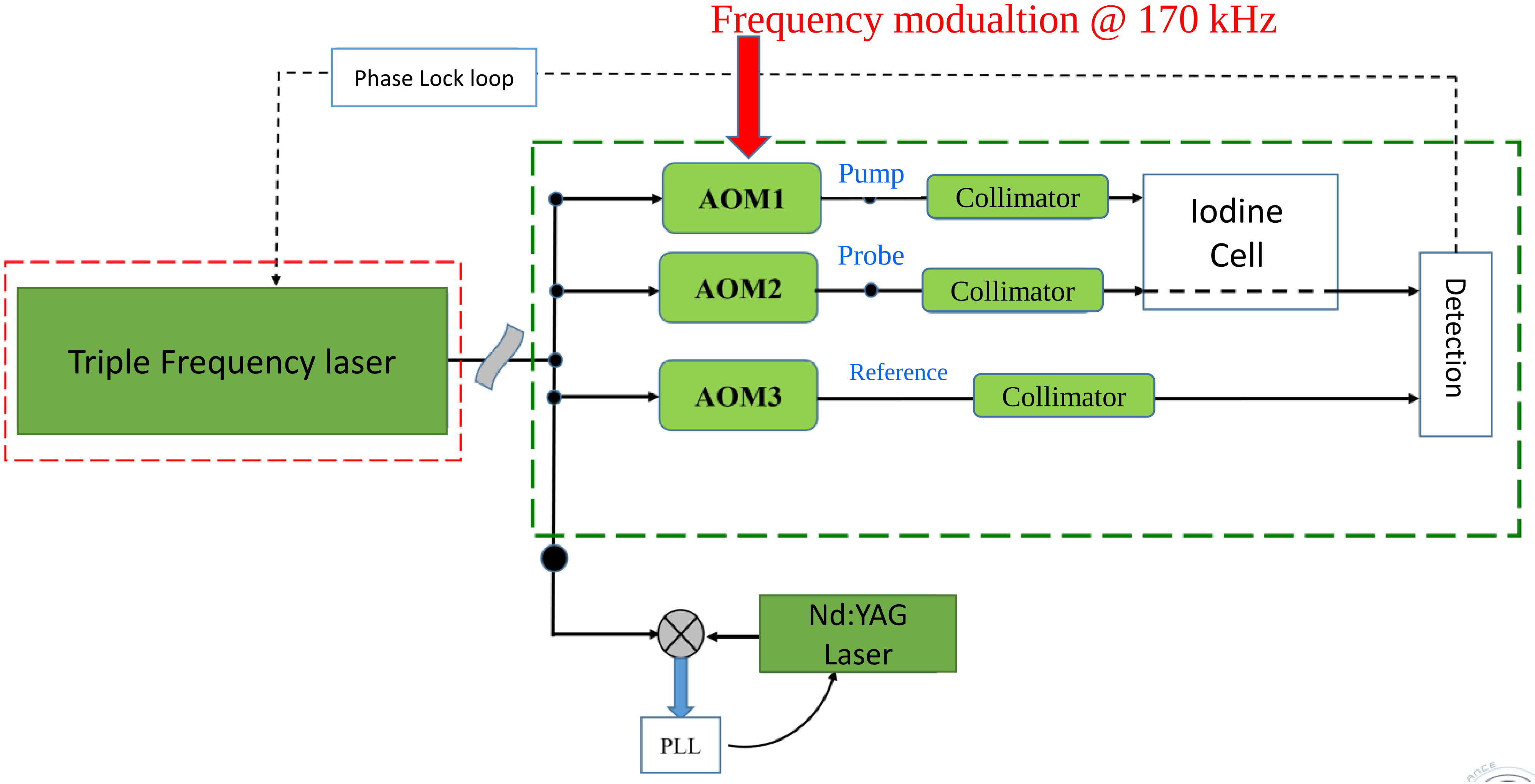
SFG (w + 2w → 3w) LiNb03 PPLN Cristal Bulk from Covesion (UK)
L= 40 mm, l= 5 mm, h = 0.5 mm
1 W à 1596 nm, 220 mW @ 798 nm → 31 mW @ 532 nm (after fiber coupling)
η ~ 4.5 % $W^{-1} * cm^{-1}$ Kylia / EXAIL (state-of-the-art)

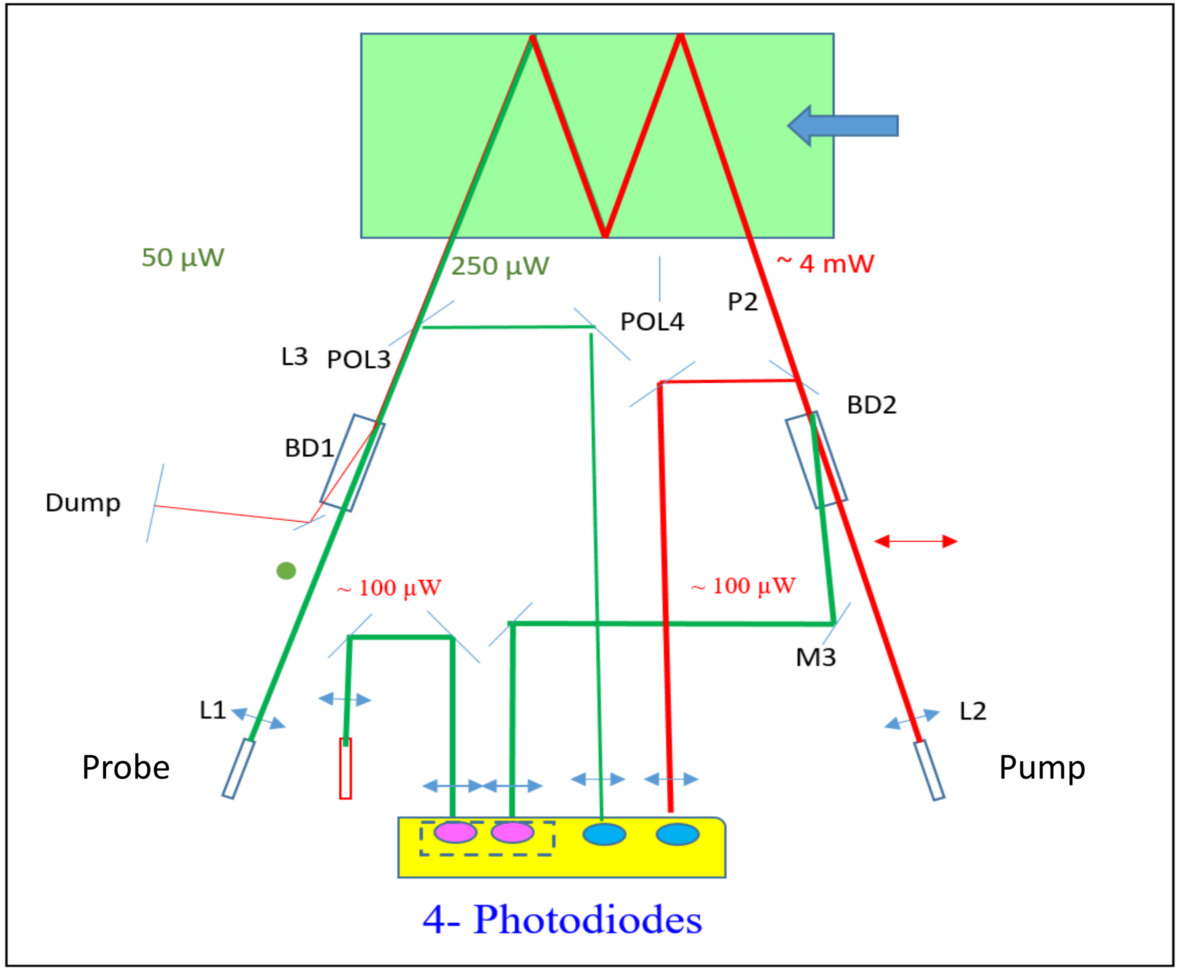
- The whole setup fit in a 15 L aluminum red case
- Every component are fibered, such as it didn’t need any alignment after transportation





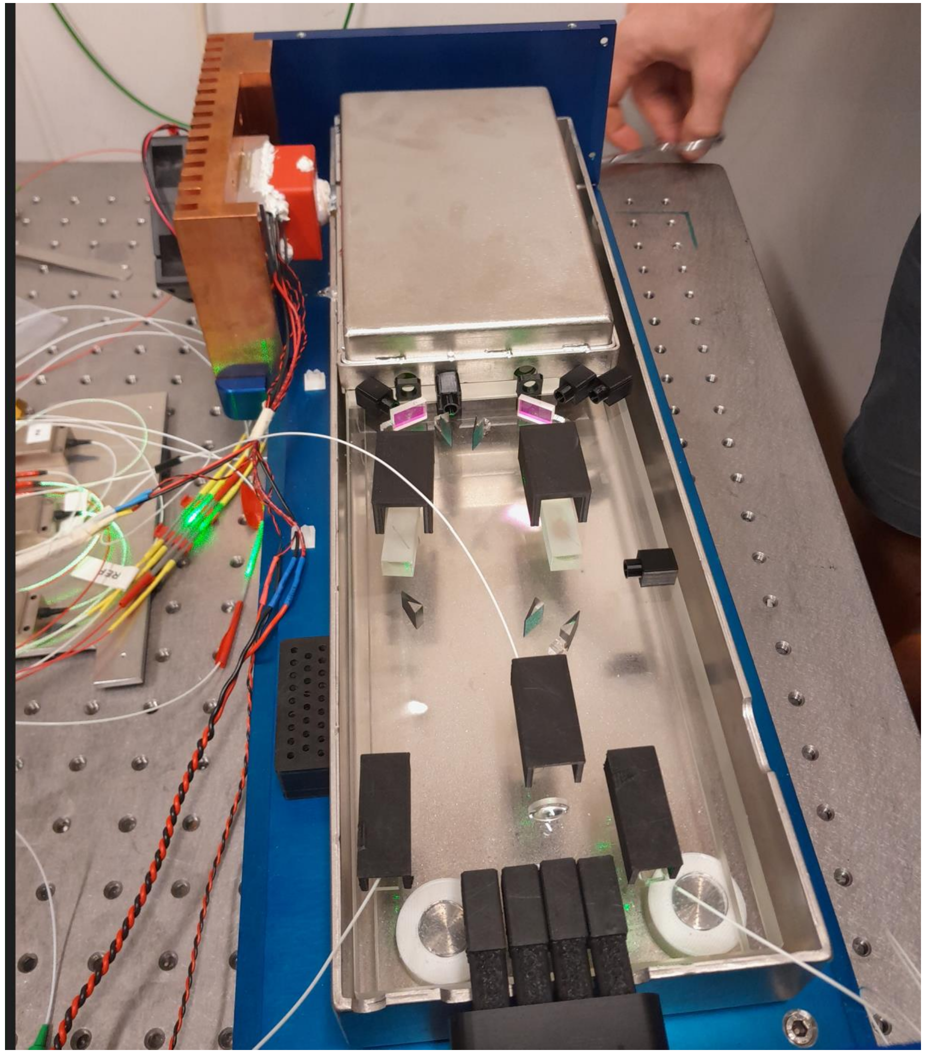
- The modulation is made on the pump AOM @ 170kHz
- The spectroscopy setup is in free-space without mechanical part.
- The signal is detected using a lock-in amplifier @ the modulation frequency.

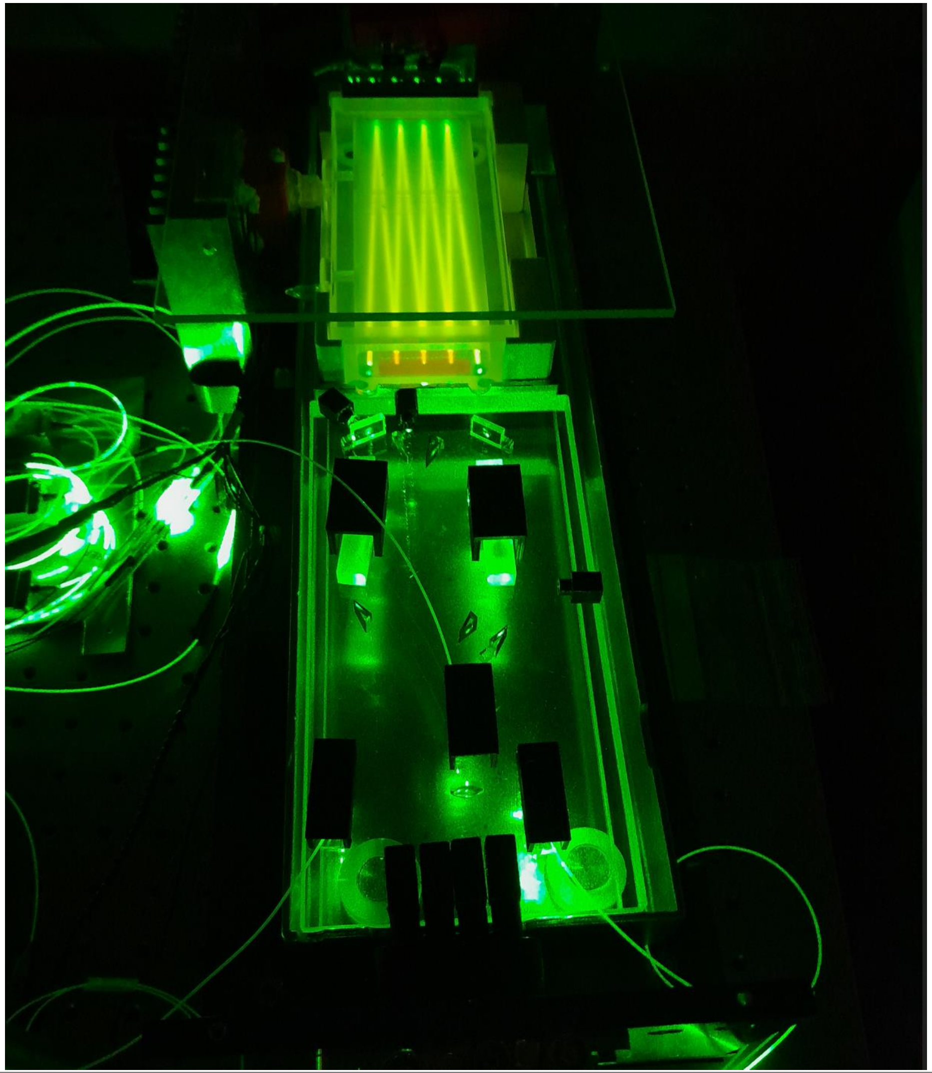


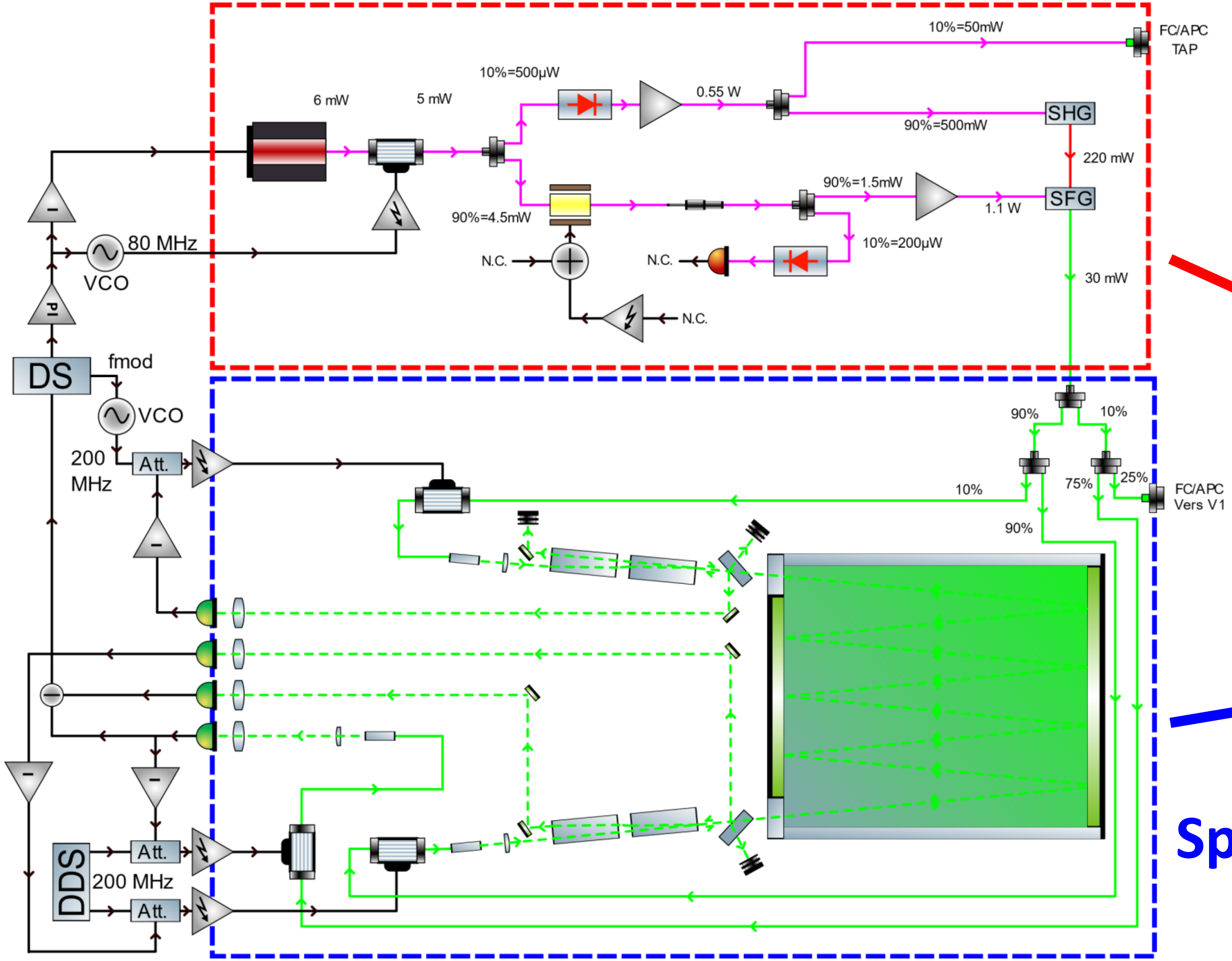


- Two counter propagating beams
- Orthogonal polarization for pump and probe beams
- Beam diameters ~ 2.4 mm, Rayleigh parameter > 2 m
- Iodine absorption length 120 cm with 8 passes
- Iodine cell dimensions: 15 x 8 x 4 cm

➢ The whole setup fit in a 15 L aluminium blue case







THG

Spectroscopie

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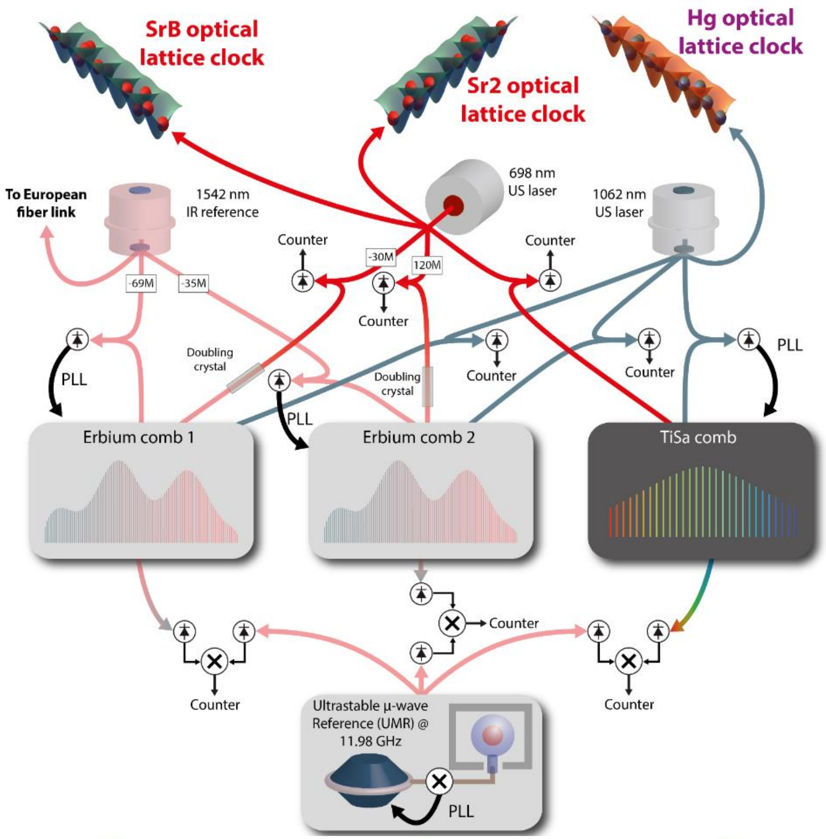
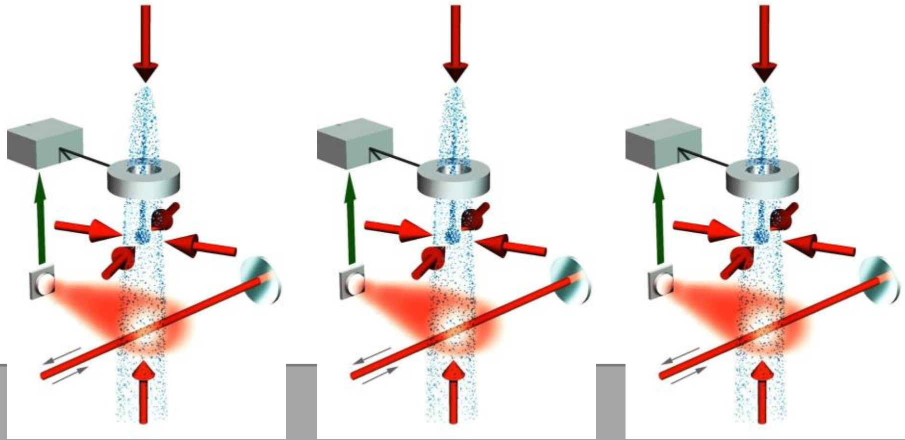
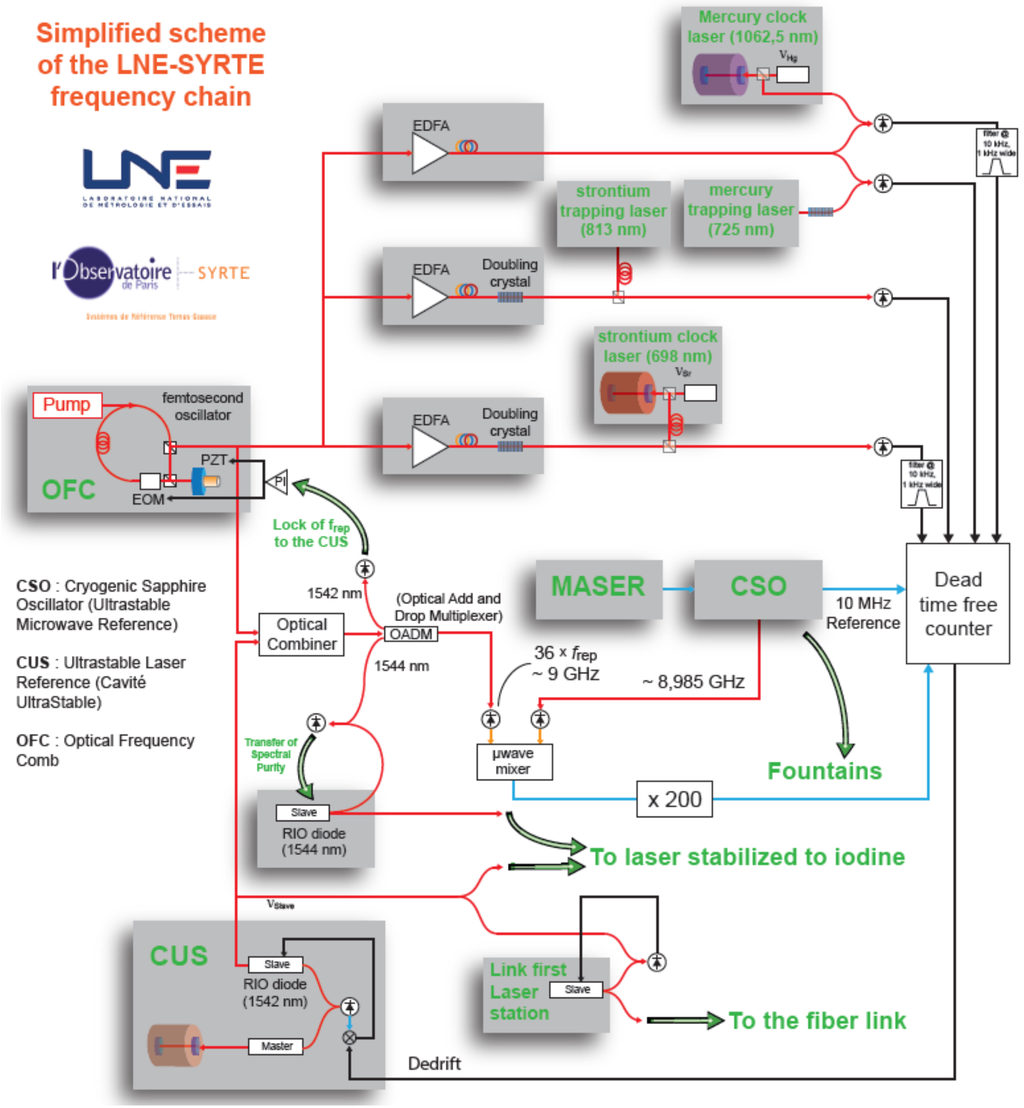
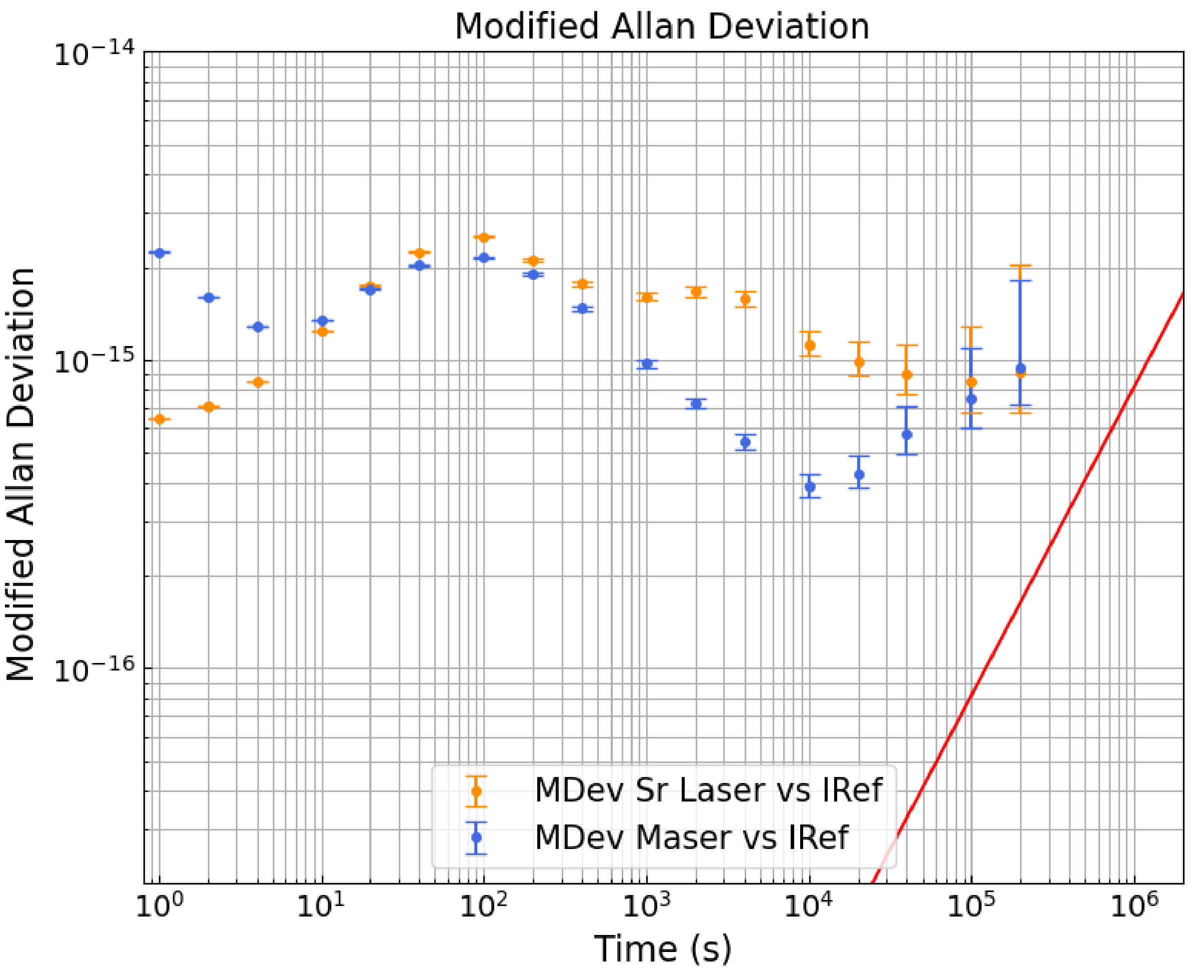


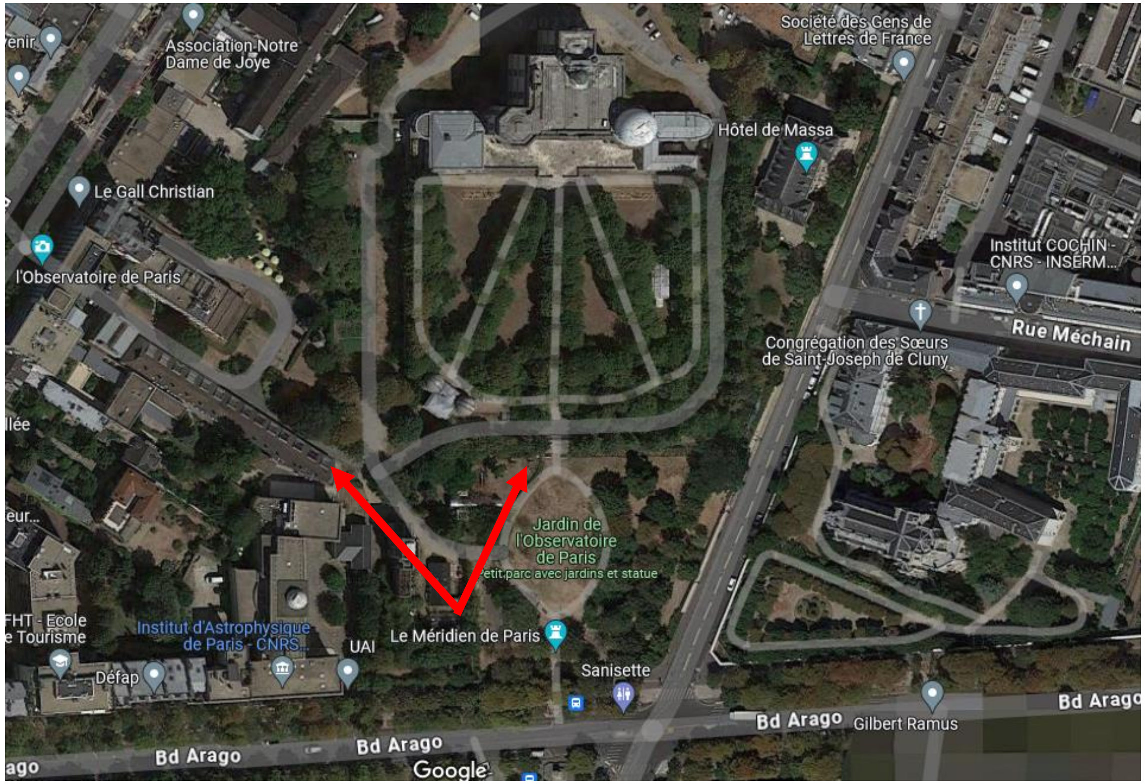


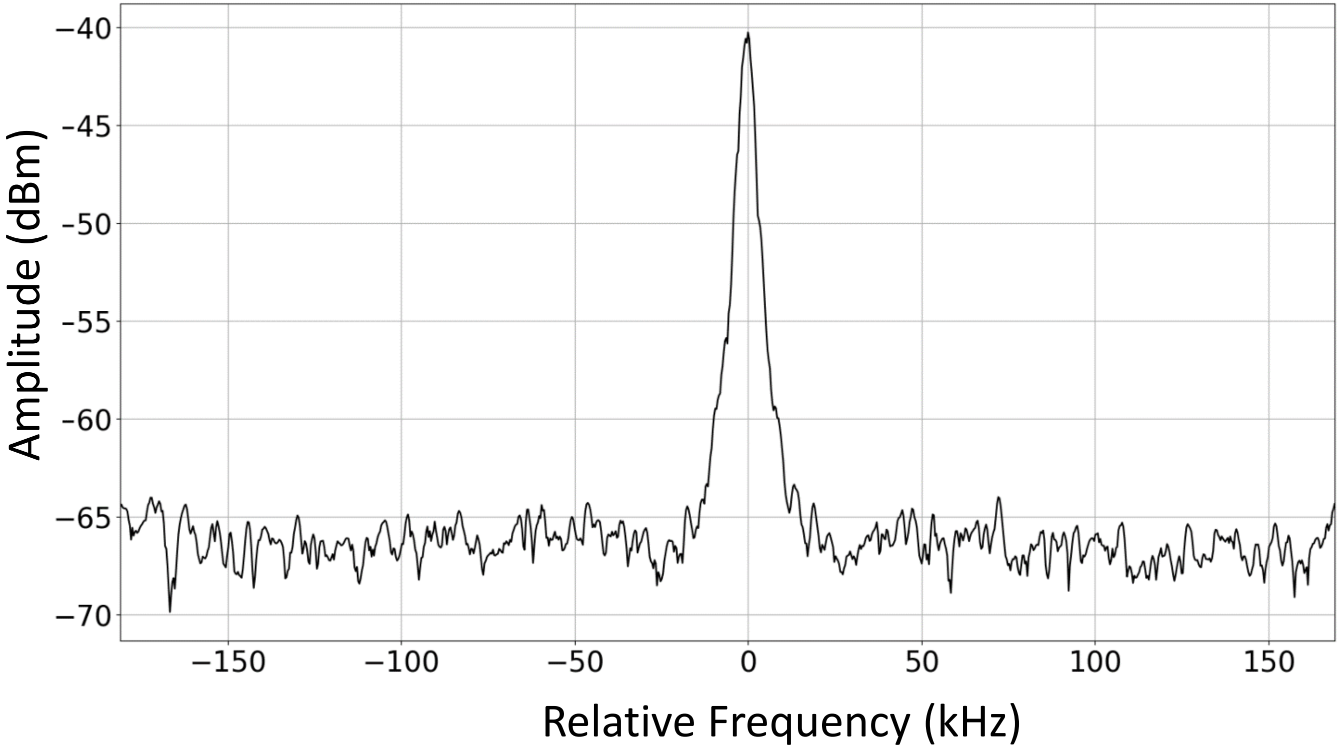
- 7 clocks at SYRTE:
  - 3×Cs (µwave, 9.2 GHz)
  - 1×Rb (µwave, 6.8 GHz)
  - 2×Sr (opt, 429 THz)
  - 1xHg (opt, 1129 THz)
  - New projects : 1xYb (opt, 519 THz) and 1×Sr (opt, 429 THz)
- Optical Frequency Combs allow us to measure optical frequencies :
  - Continuous measurement of frequency ratios
  - Sampling rate : 1pt/s
  - At SYRTE: 2 Erbium fiber laser based combs
  - The 1542 nm source is critical
    - Er combs locked to this optical reference
    - Source for the REFIMEVE network



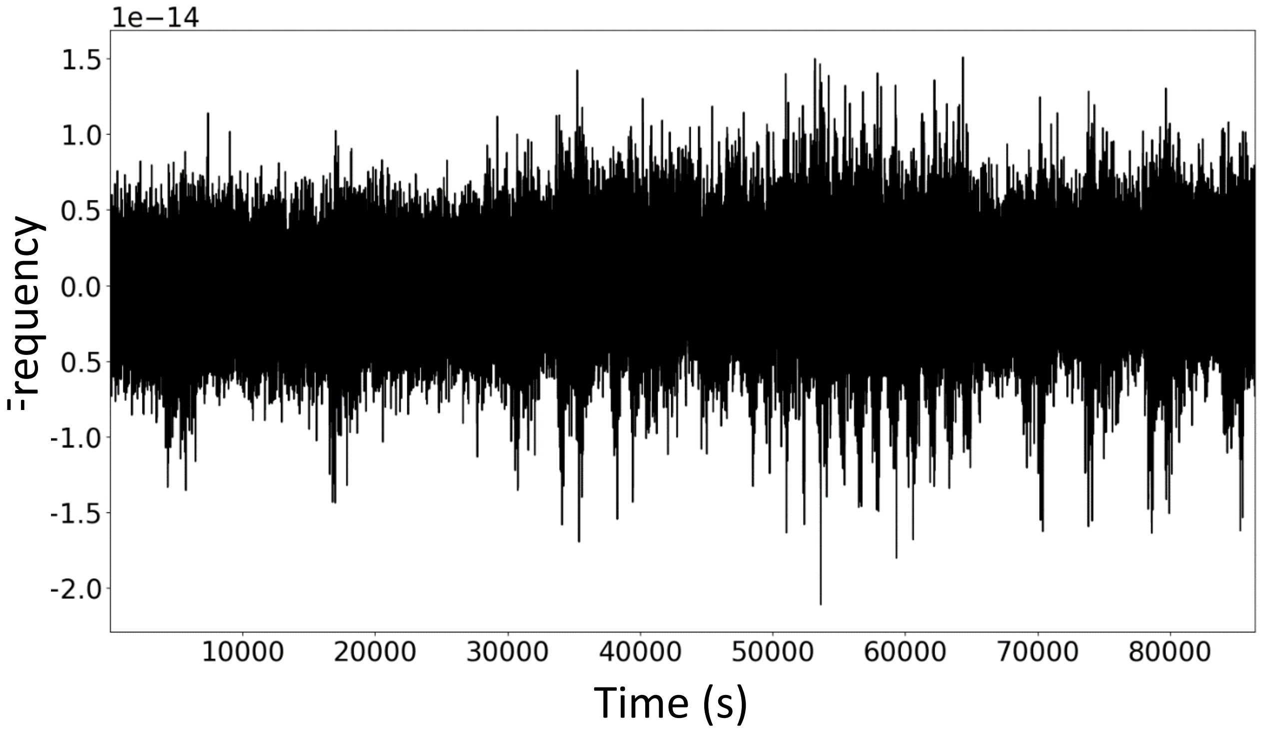


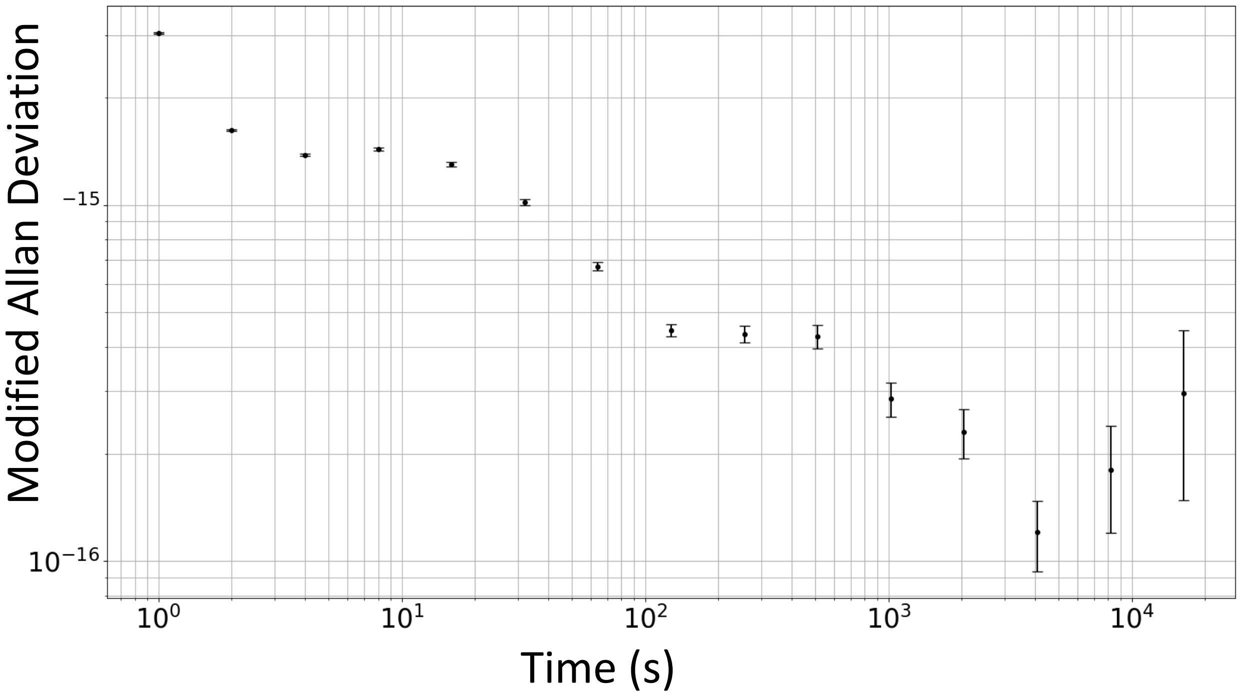
- Sy(f) : 30 Hz/√Hz => Adev @1s : <8e-14





A 200 m un compensated fibered link

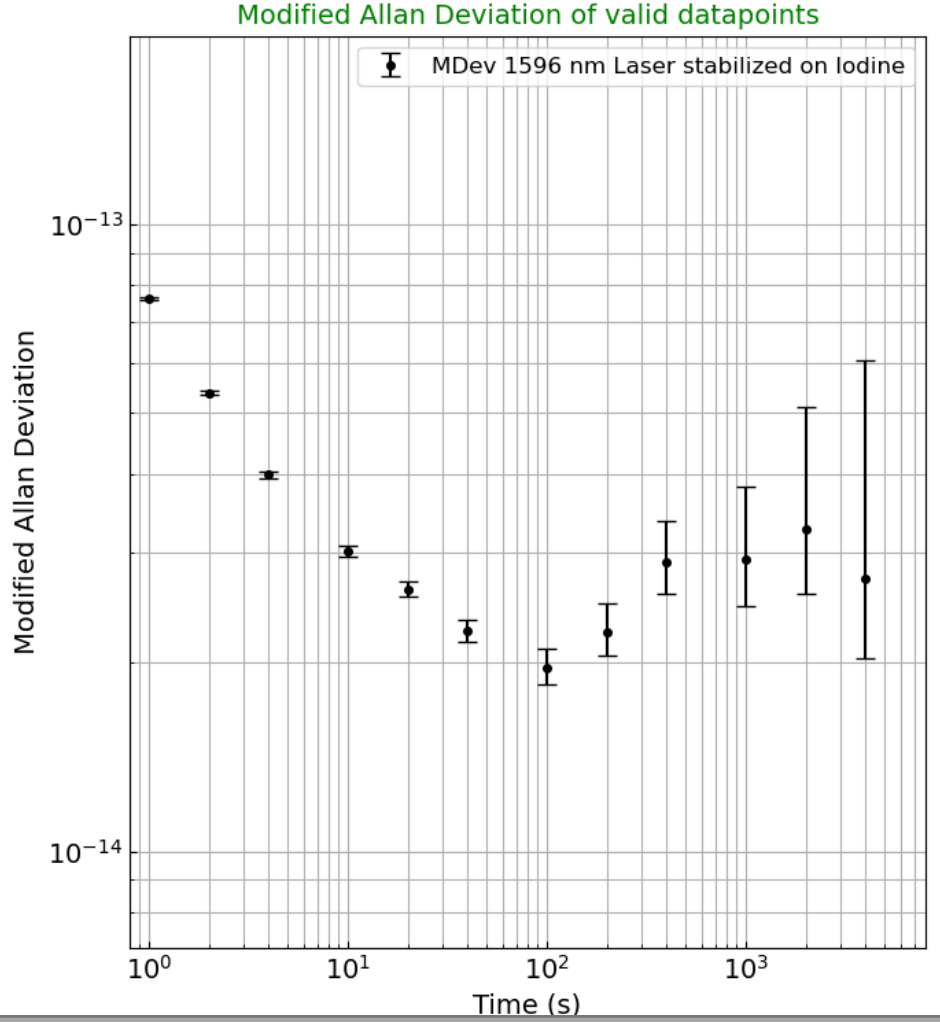


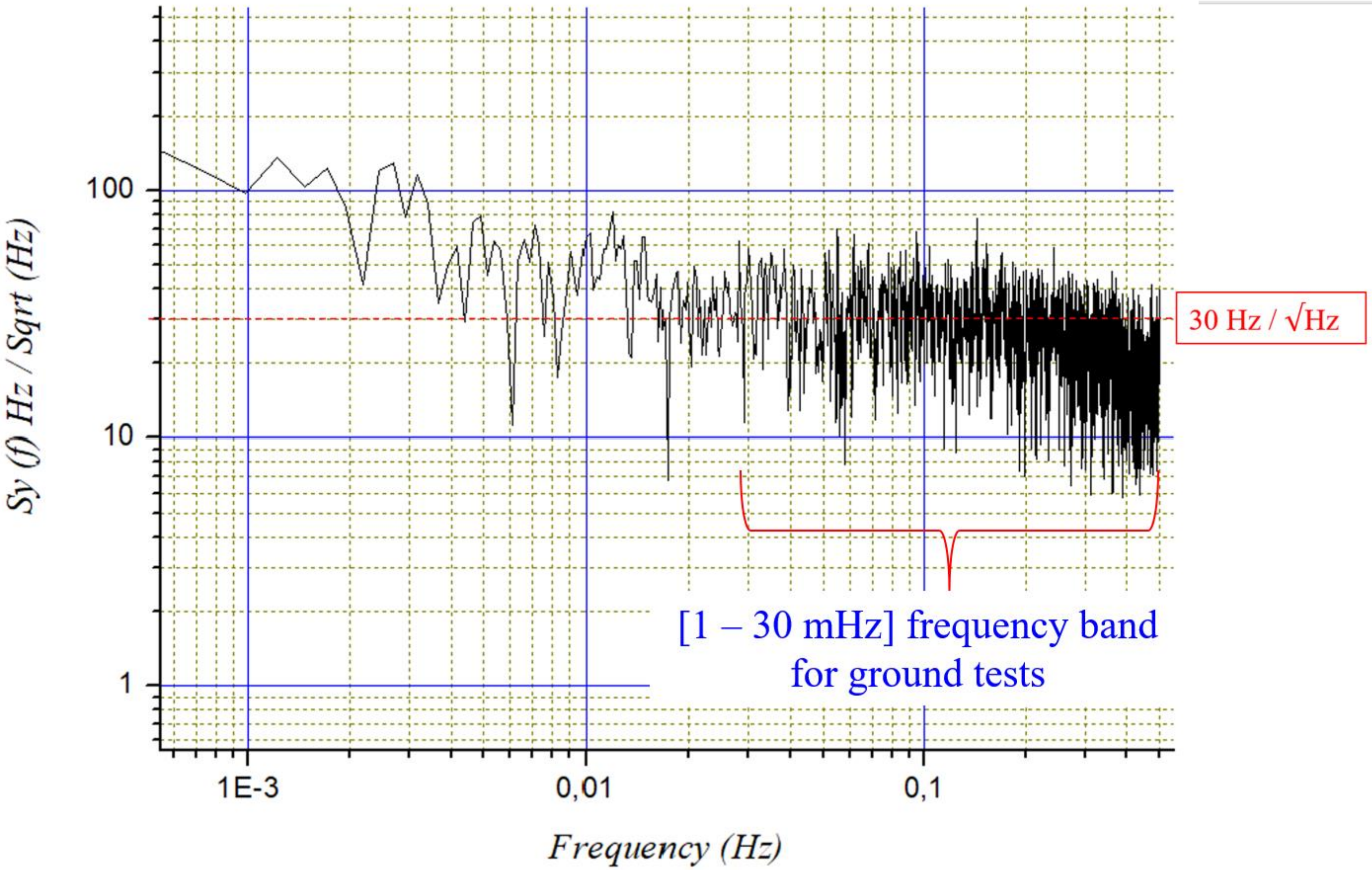


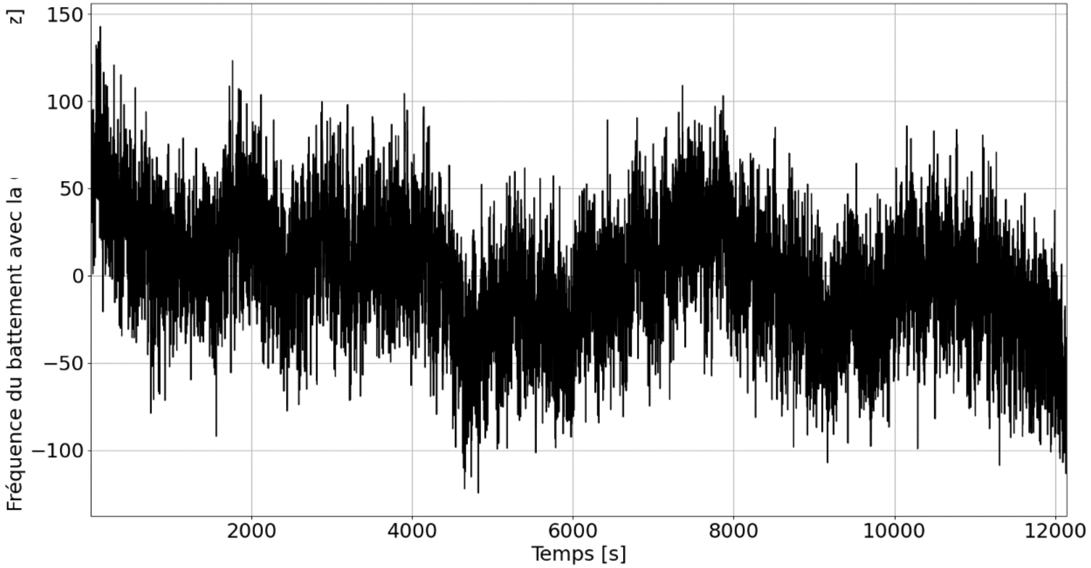
- Adev @1s : 3e-15 < 8e-14

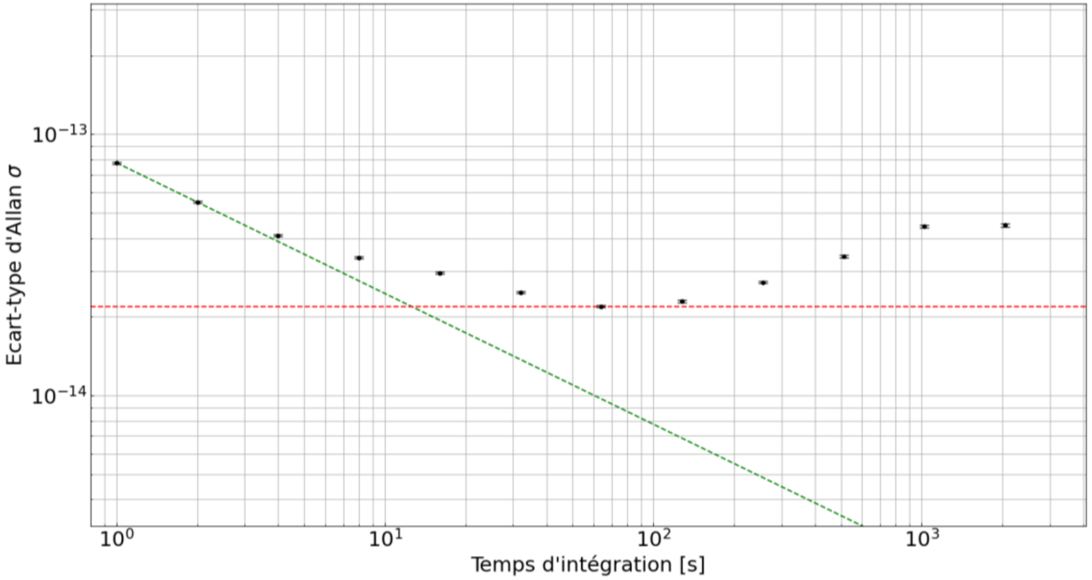
The link is below the Lisa mission specification so it will not limited the comparison between the comb and the laser

- Tracking Oscillator and 100kHz Bandpass filter
- Measure vs LTE IR 1542 nm Laser : Adev @1s : 7-8e-14
- Sy(f) : 30 Hz/√Hz









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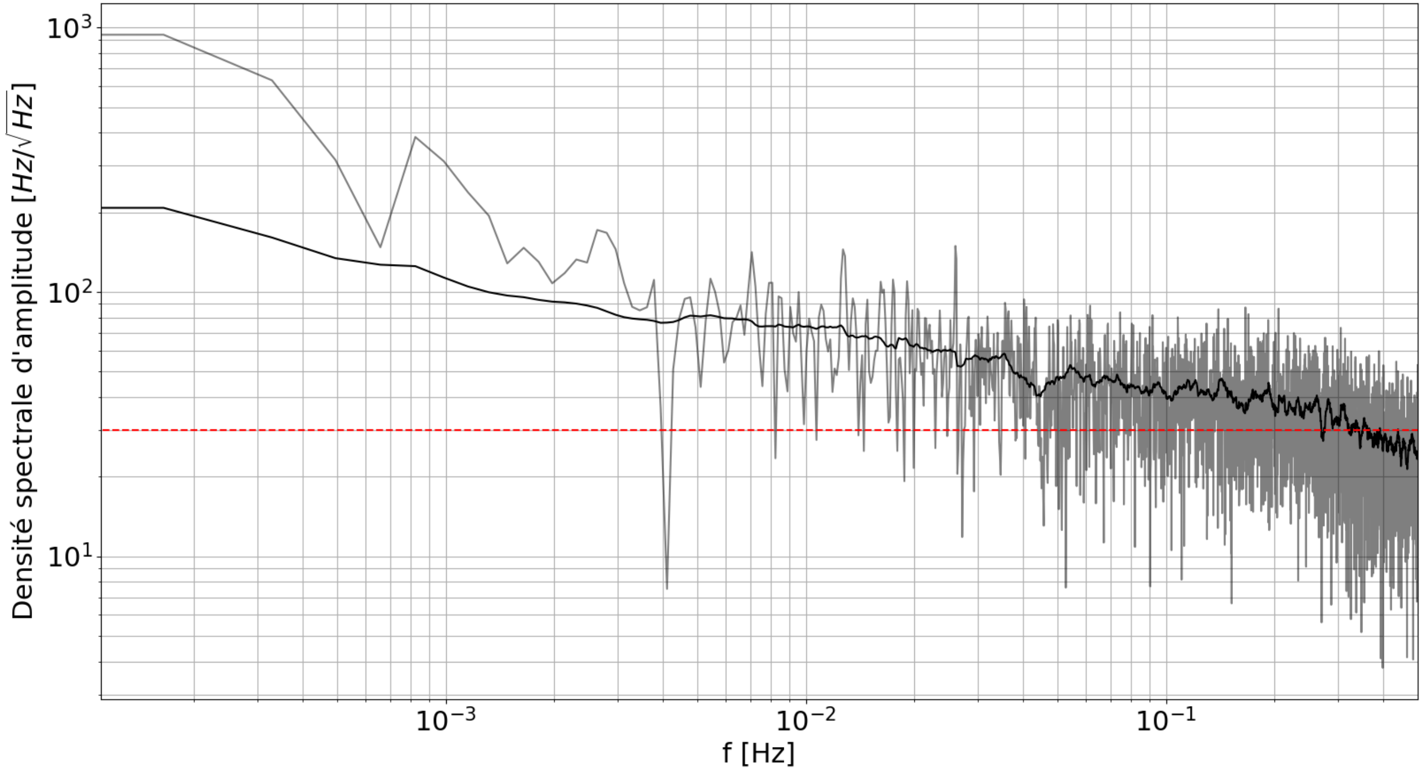

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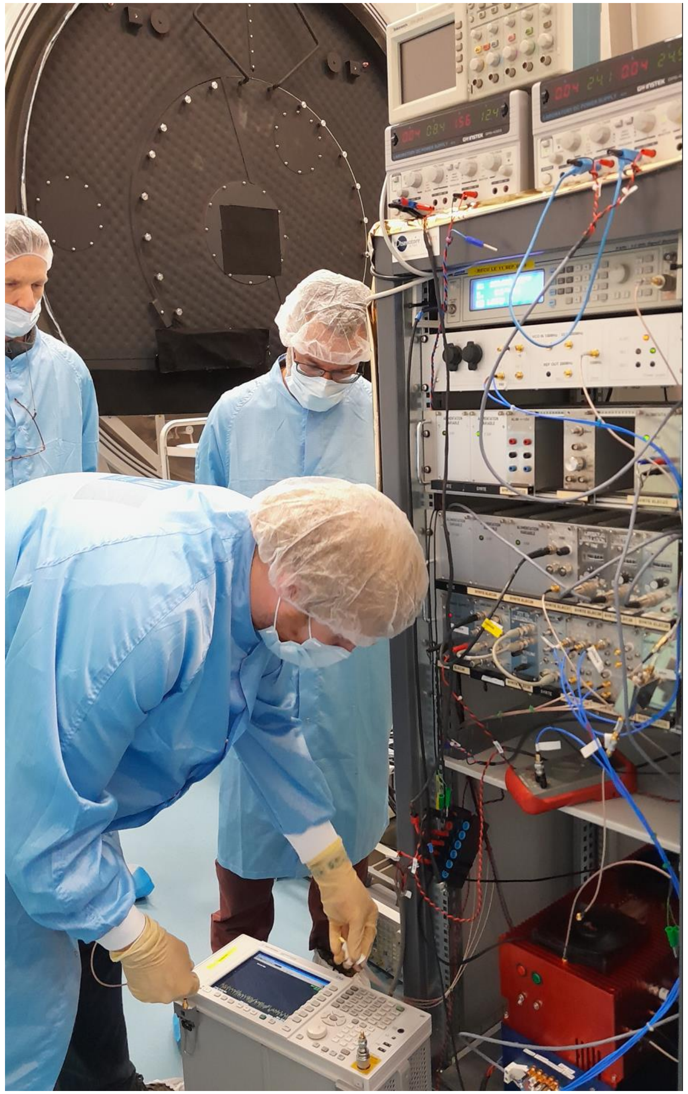
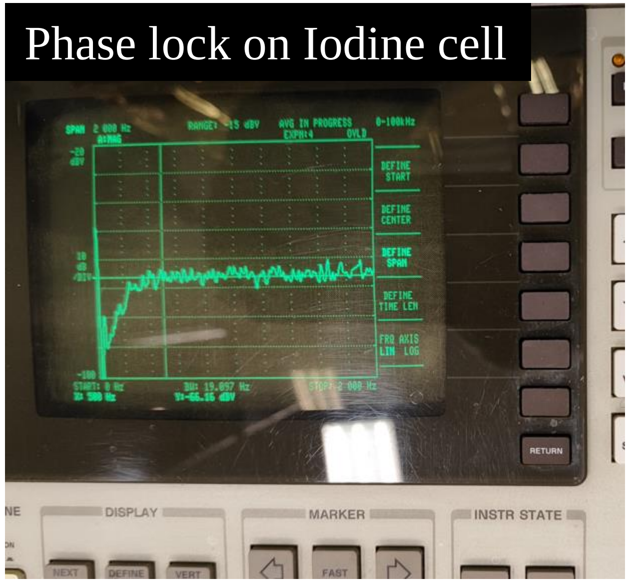
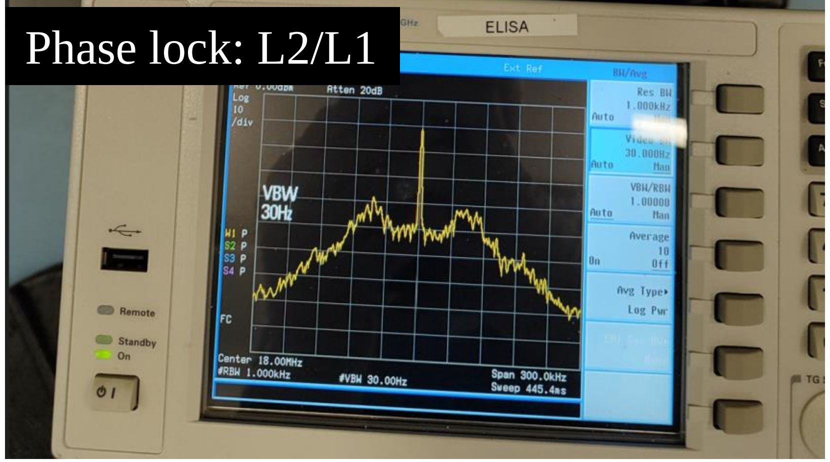
- Moving of the laser Setup to LAM (Marseille)



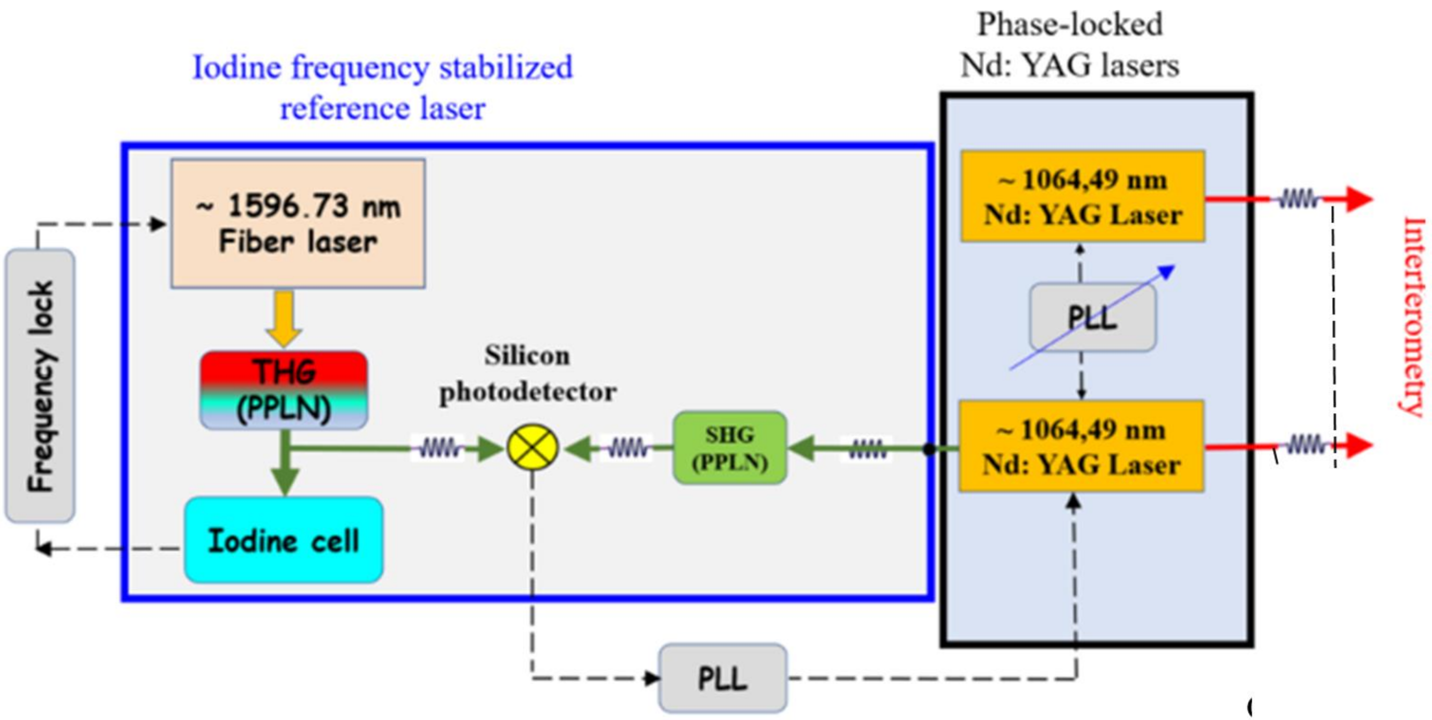
- The reference laser and every different phase lock were operational in less than 2h at their nominal level

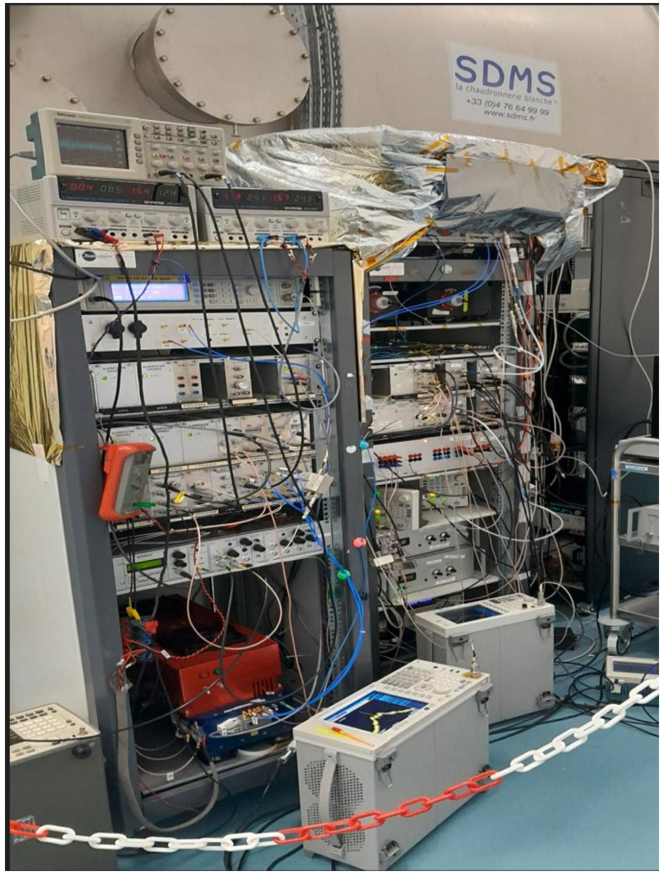

Phase lock on Iodine cell


Phase lock: L1/Iode


Phase lock: L2/L1

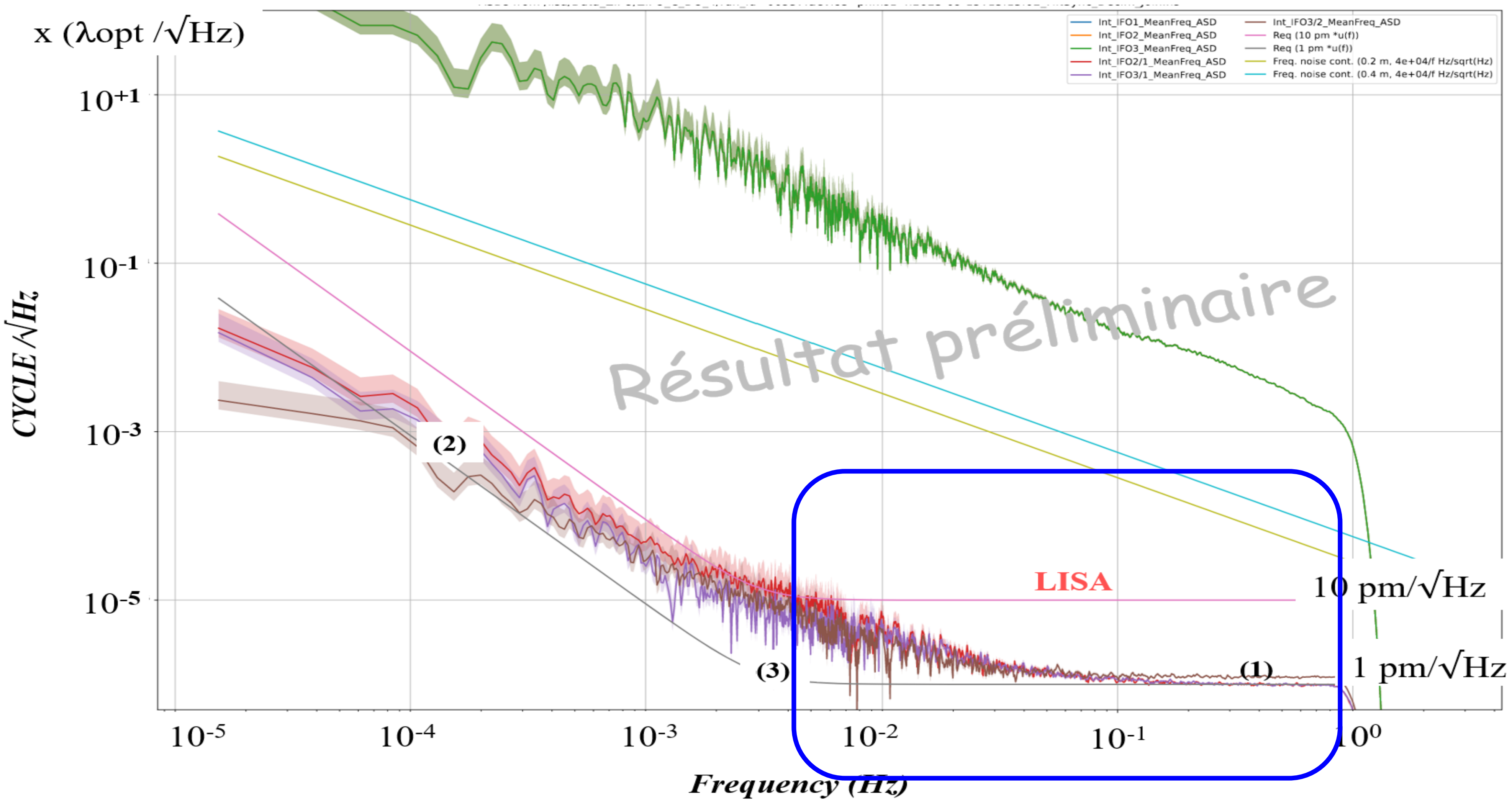
- We were able to operate all the Laser for all the duration of the test without any unwanted interruption





- **Iodine Frequency Stabilized Laser (L0) didn't need any intervention**
- **Same for the master Nd:YAG Laser (L1) phase lock on L0**
  From 06/07 to 13/07 (Installation Time)
  From 26/08 to 08/09 (Preleminary Test)
  From 10/09 to 28/09 (Measurements Campaign)
- **Phase lock of the Laser L2 on L1 : ON / OFF every 15 h for the need of the test**

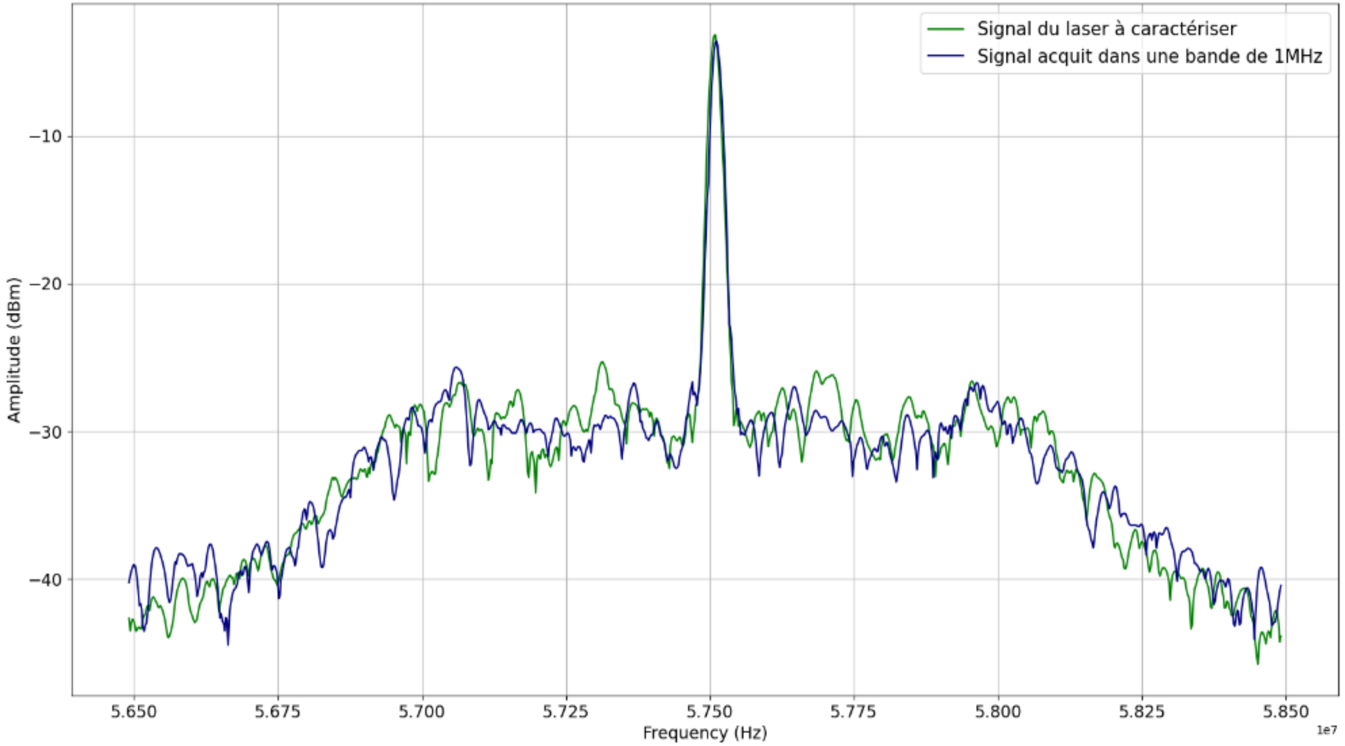
- Measurements achieved at LAM by the consortium: APC, ARTEMIS, CEA, CNES, CPPM, LTE



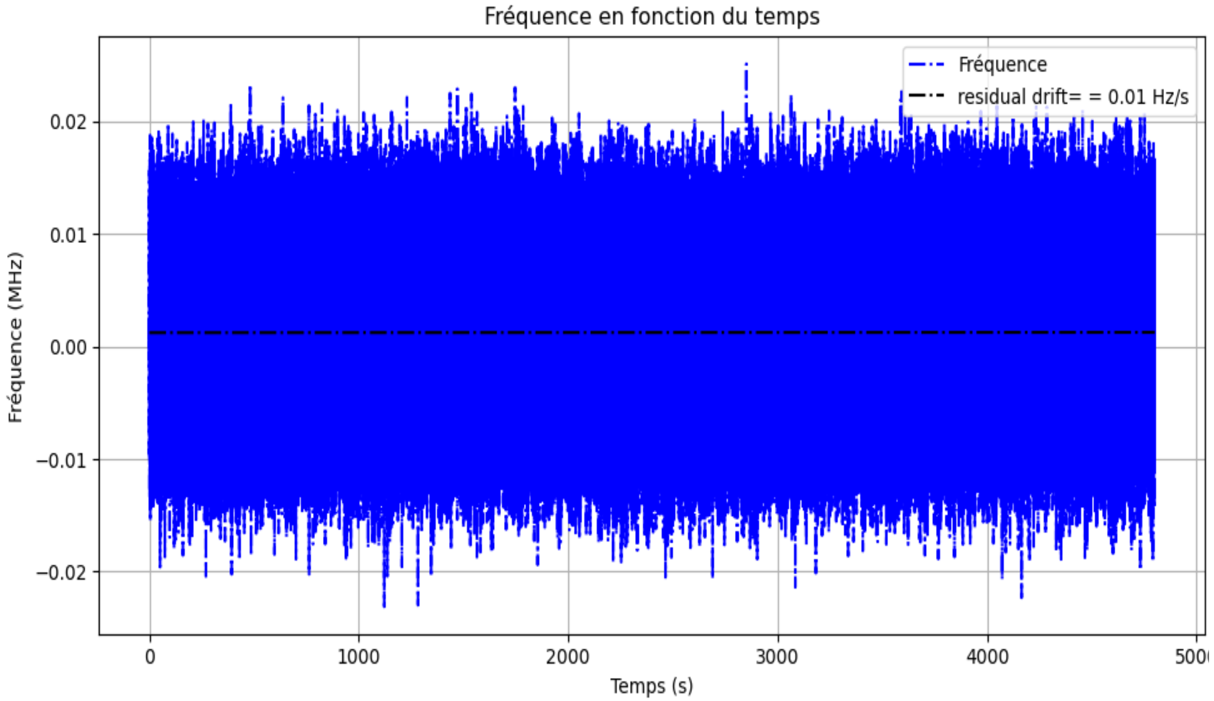
Conclusion ?

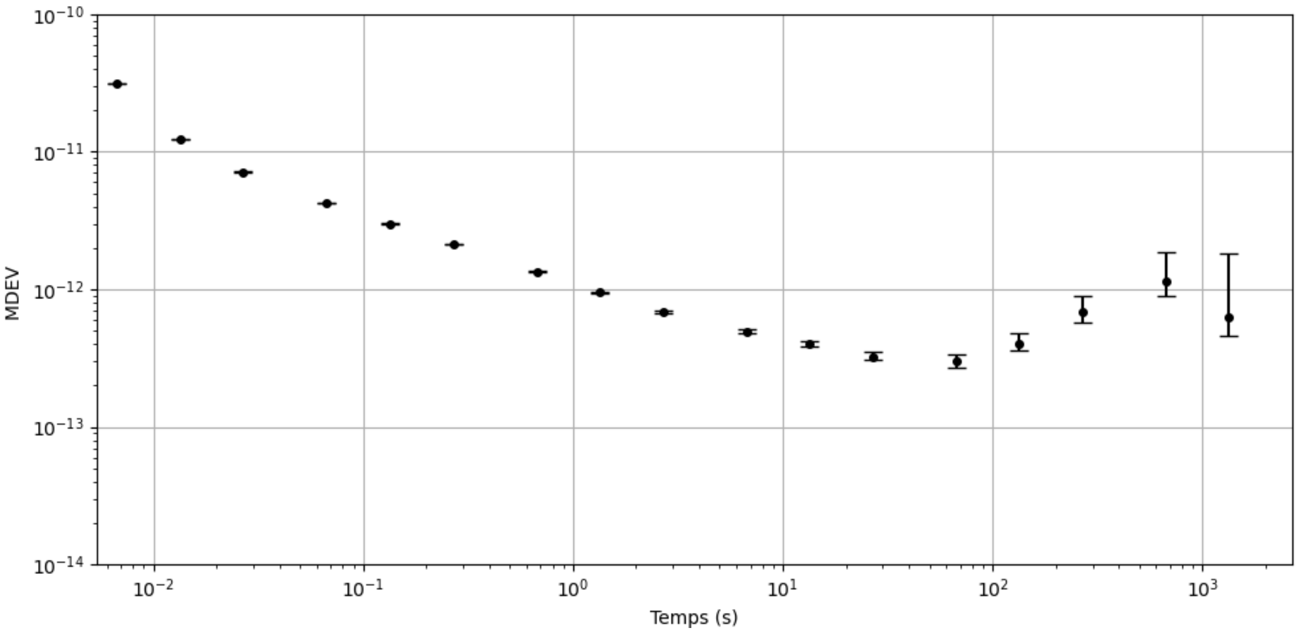
- We have developed a compact, fully fibered and transportable optical frequency standard emitting at 1596 nm and 532 nm.
- A tandem of Nd: YAG laser at 1064.49 nm are phase locked to this iodine reference, using additional SHG crystal and PLL.
- The whole setup has been used successfully for ground tests of the LISA space mission, led by the CNES agency.
- A industrial transfer with Exail is in progress and will need new characterization in 2026
- Open a new path toward characterization of few 100Hz to few kHz linewidth lasers using the optical frequency chain at LTE

- For the 2026 measurements, we investigate a new integrated FPGA-based solution : a Phasemeter with a tracking oscillator proposed by Liquid Instrument via the Moku:Pro
- Bandwidth of 1 MHz for the loop



- First results with the laser prototype showed a degradation of the performance possibly due to the multiple transportations





- The acquisition of a dedicated MokuPro has been half-funded by First TF under the CARAMEL project
- Need to investigate more to find the cause of the degradation

Thank you for your attention