Assemblée générale FIRST-TF

Rennes – 8 octobre 2025

Vers une technologie CSO de 3[eme] génération

(CSO 3G)

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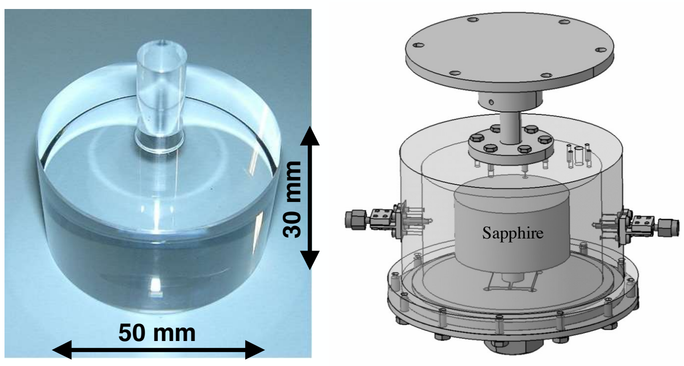
Projet soutenu par FIRST-TF

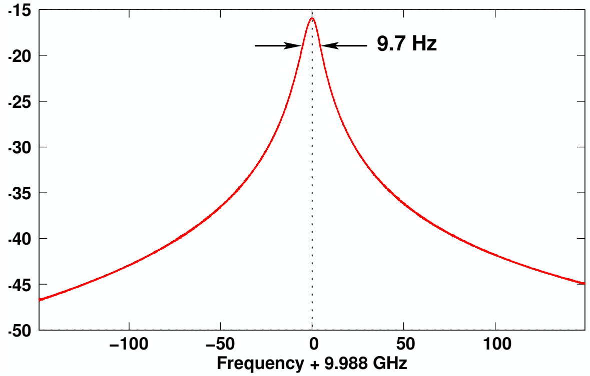
2021 : 60 k€
2024 : 14.5 k€
2025 : 12 k€ + (20 k€)

Oscillateur Saphir Cryogénique (CSO)

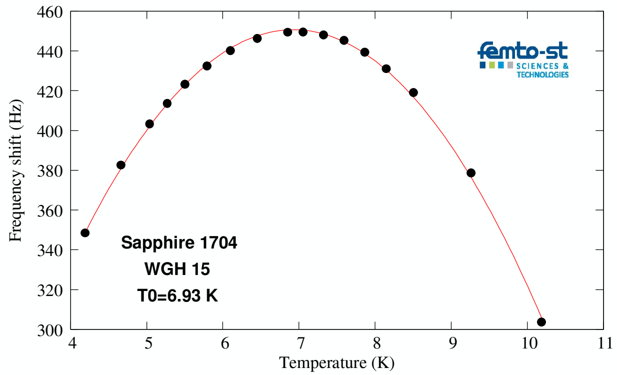
9.99 GHz resonator

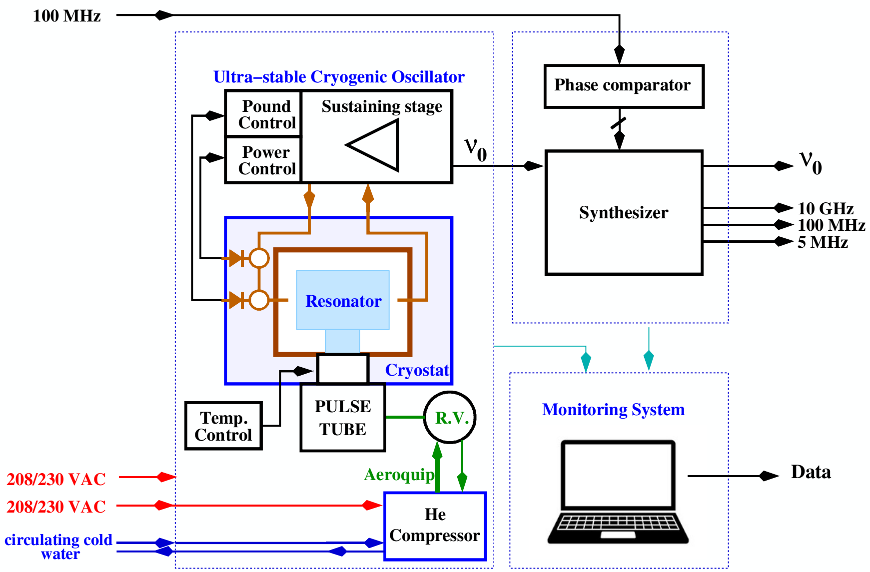


$Q_L \approx 1x10^9$



Turnover 5-8 K

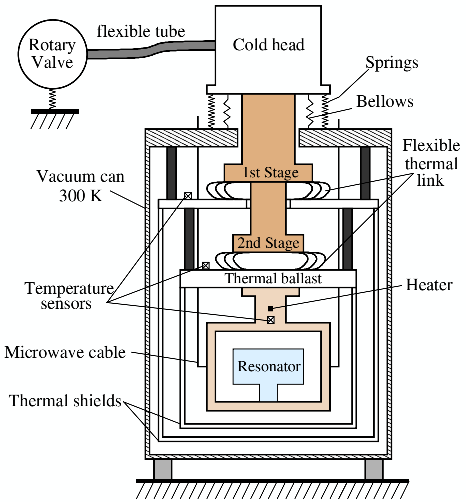




https://www.femto-engineering.fr/realisation/oscillateur-cryogenique-ultrastable-uliss/

ULISS-2G : Cryo. “Basse consommation”
ANR Emergence 2012

Cryomech PT 403
(3 kW) 250 mW @ 4 K

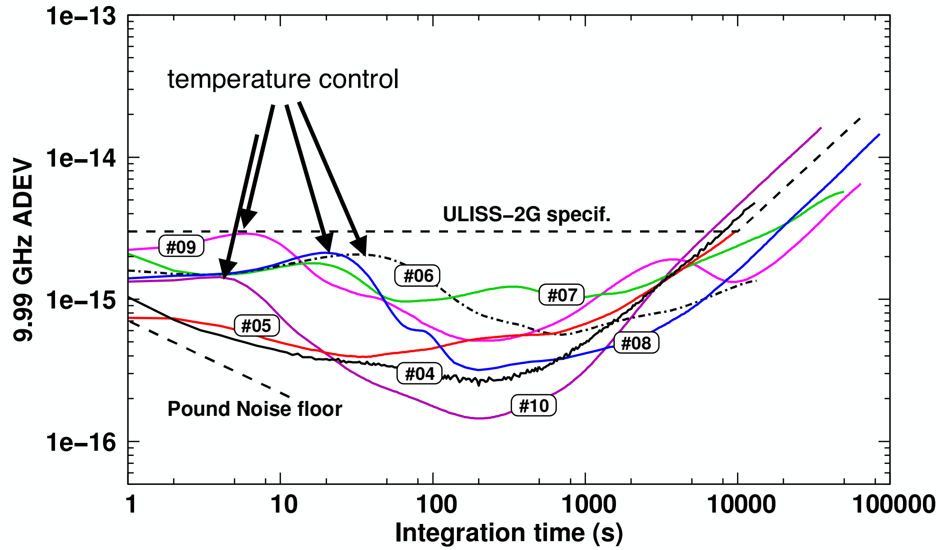


Compromis entre T mini et isolation des vibrations

12 CSOs « autonomes » construits et validés à FEMTO-ST depuis 2009

#	Nickname	Power	First operation	Status	Who
000	ELISA	6 kW, 3-phase	June 2009	Prototype	ESA
001	MARMOTTE	6 kW, 3-phase	Oct. 2010	Oscillator IMP reference	FEMTO-ST
002	ULISS	6 kW, 3-phase	Nov. 2011	Oscillator IMP reference, transportable unit	FEMTO-ST
003	ABSOLUT	8 kW, 3-phase	May 2014	Oscillator IMP reference	FEMTO-ST
004	ULISS-2G proto	3 kW, 1-phase	June 2015	Prototype, proof of principle	FEMTO-ST
005	ULISS-2G 005	3 kW, 1-phase	Dec. 2017	Commercial, delivered	USNO
006	ULISS-2G 006	3 kW, 1-phase	Nov. 2018	Commercial, delivered	USNO
007	ULISS-2G 007	3 kW, 1-phase	June 2019	Commercial, delivered.	USNO
008	ULISS-2G 008	3 kW, 1-phase	Dec. 2020	Commercial, delivered	NTSC
009	ULISS-2G 009	3 kW, 1-phase	April 2021	Commercial, delivered	NPL
010	ULISS-2G 010	3 kW, 1-phase	March 2022	Commercial, delivered	INRIM
011	ULISS-2G 011	3 kW, 1-phase	March 2024	Commercial, delivered	KRISS
012	ULISS-2G 012	3 kW, 1-phase	– –	Commercial, under construction	SYRTE

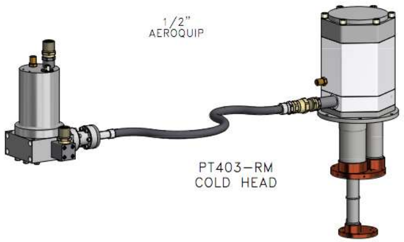
ULISS 2G ADEV



Projet FIRST-TF 2021

Disponibilité d'un PT "faible conso" ?

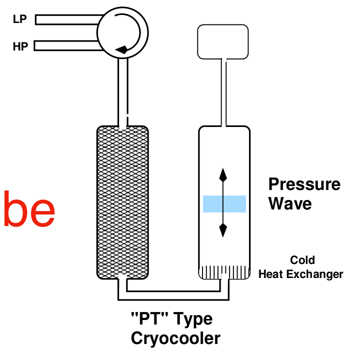
Conception ULISS-2G basée sur PT 403 (CryoMech)



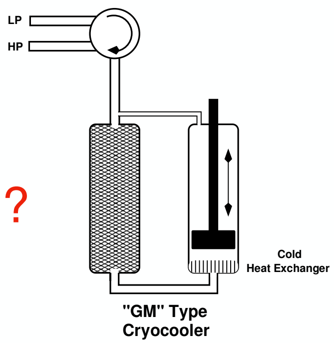
Pas d'autre cryo. équivalent sur le marché

Two types of 4 K Cryocooler:

Pulse-Tube



GM ??



Mouvement d'une onde de pression

Pas de pièces mobiles à froid

Maintenance réduite, vibrations limitées

+ Disponible chez de nombreux fabriquants

+ Gamme étendue de puissance de refroidissement

+ Produit en plus grandes quantités

+ Fonctionne quelque soit orientation

- Vibrations induites par le piston

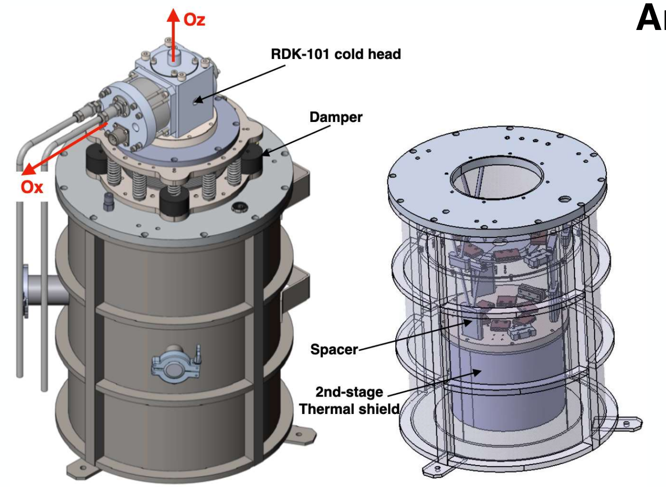
- Maintenance

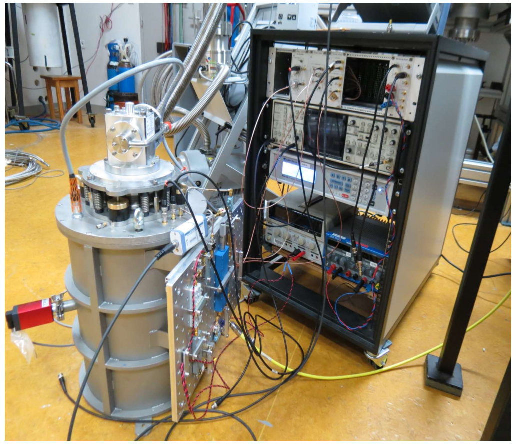
Nouvellle conception du cryostat ULISS-3G

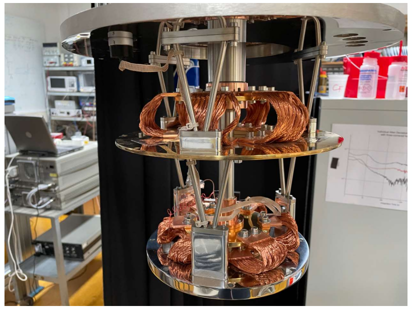
Enceinte rigidifiée, Tubes 6 × 5.7 mm

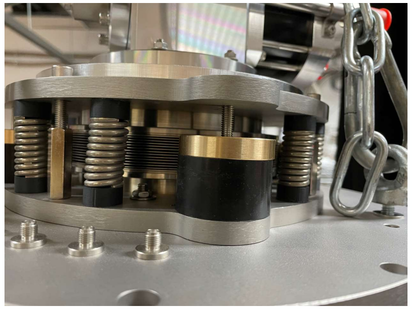
Ecrans Cu dorés

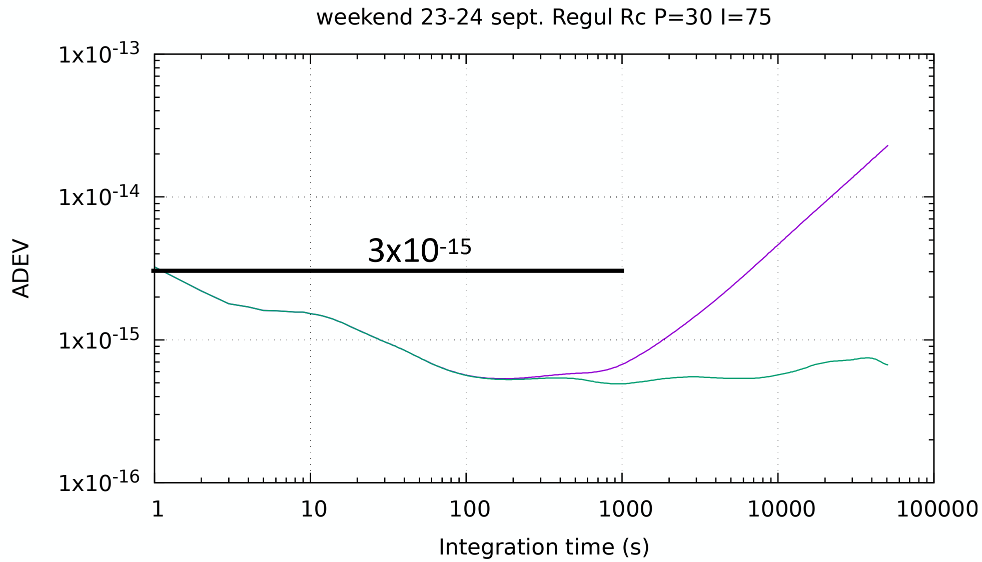
Ammortisseurs Sorbothane











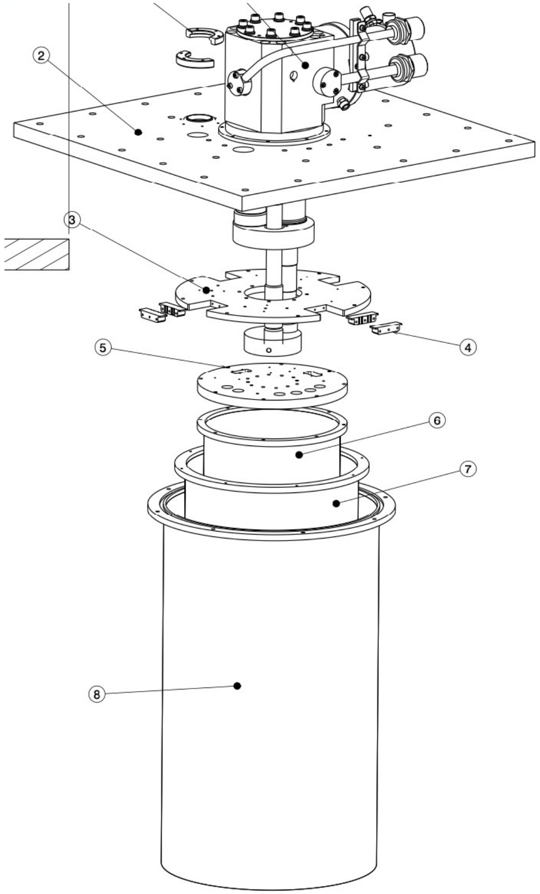
Ultra-Stable Microwave Cryogenic Oscillator operated with a Gifford-McMahon cryocooler

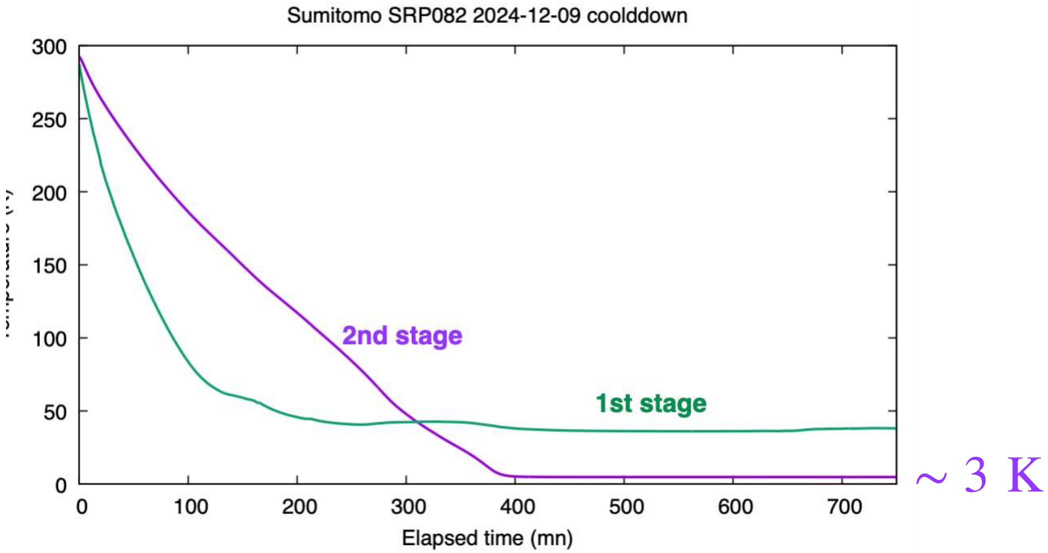
G. Le Tetu, C. Fluhr, B. Dubois, J. Paris, R. Hostein and V. Giordano.
Cryogenics, 135 (2023), 103745, DOI : 10.1016/j.cryogenics.2023.103745

Projet FIRST-TF 2024

Réhabilitation d’un ancien cryostat pour test de résonateurs saphir

Sumitomo SRP082 1W @ 4.2 K





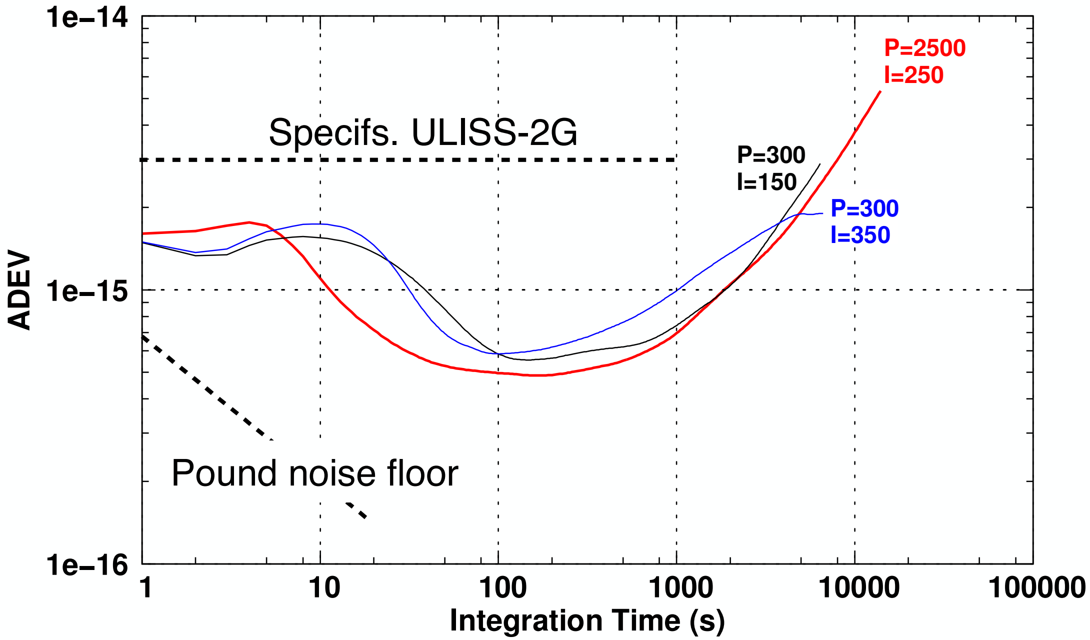
Disponible pour toutes mesures à basse température

Projet FIRST-TF 2025

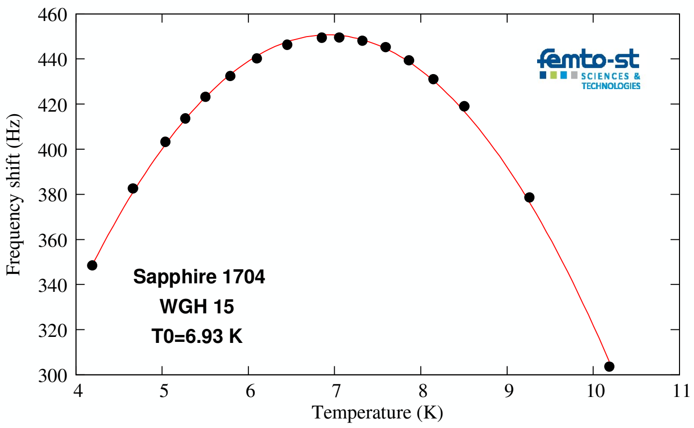
- Améliorer notre compréhension des phénomènes qui limitent la stabilité de fréquence des CSOs

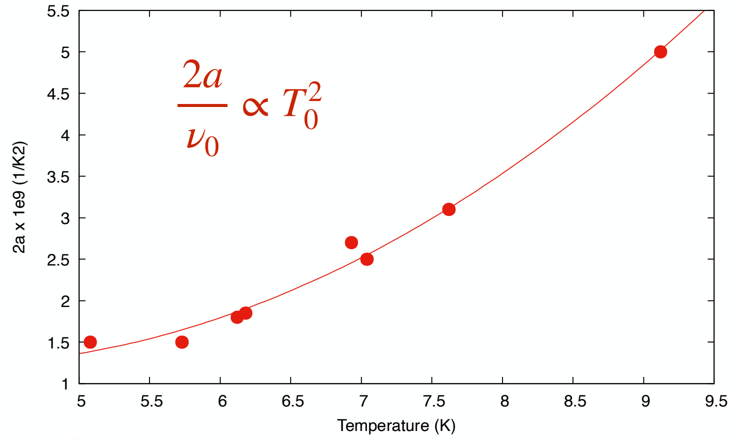
- Si possible, proposer des solutions

Pb #1 : Fluctuations résiduelles de la température

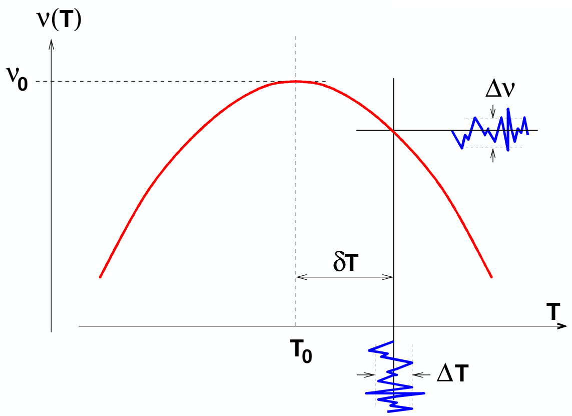


Ajustement des paramètres PI - ULISS-2G 010





$$\nu(T) - \nu_0 = a(T - T_0)^2$$



courbure

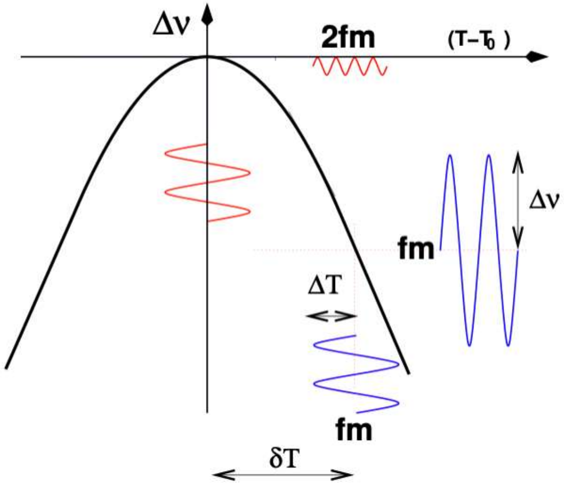
2.5x10^{-9} K^{-2} @ 7 K

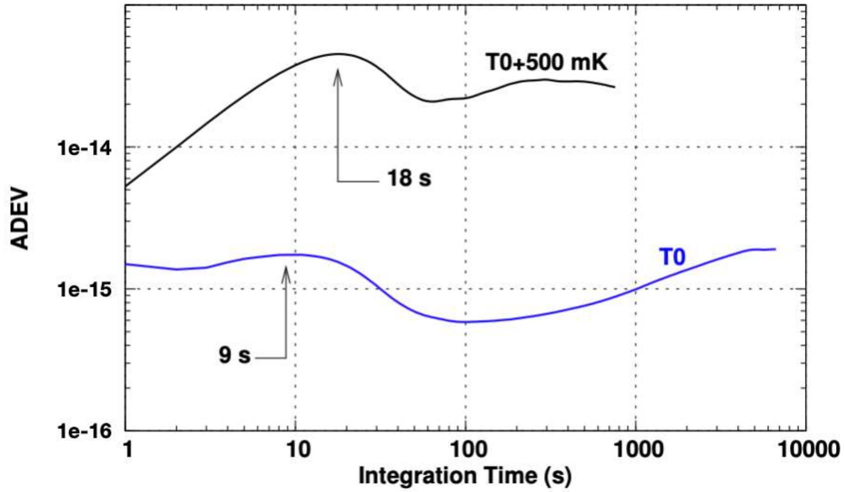
$$\frac{\Delta\nu}{\nu_0} = \frac{2a}{\nu_0}\,\delta T \Delta T$$

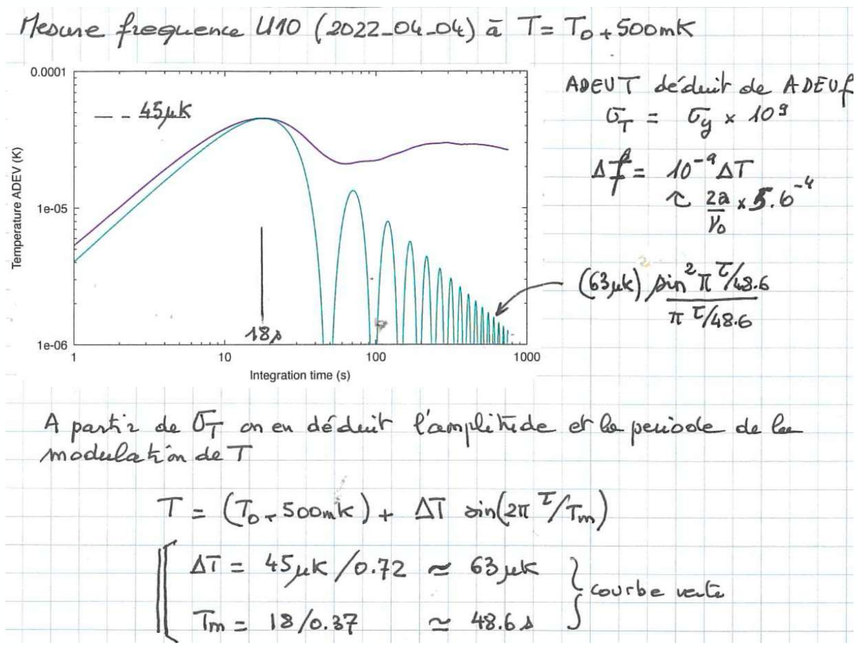
LAKESHORE 350 + Cernox 1070 @ 7 K

$$\delta T \approx 1 \text{ mK} \;; \quad \Delta T \approx 0.2 \text{ mK} \;\rightarrow\; \frac{\Delta\nu}{\nu} \approx 5 \times 10^{-16}$$

Détermination expérimentale des fluctuations de température





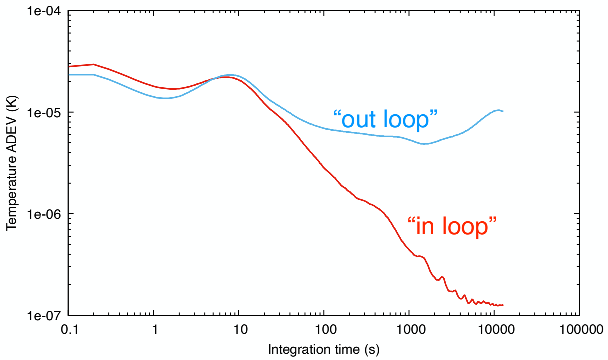


$$\text{if } T = T_0 \rightarrow \ \sigma_y^{max} = \frac{2a}{\nu_0}\frac{\Delta T^2}{\pi} \approx 3 \times 10^{-18}$$

Chercher l’erreur ??

1/ Fluctuations de T réelles ≠ déterminées par la méthode précédente ??

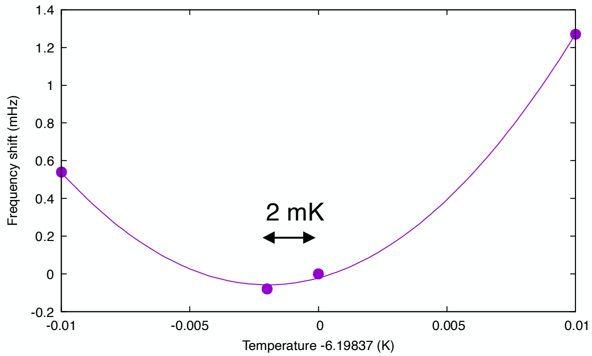
Mesures avec sonde “out loop”



2/ Erreur sur la température d’inversion ??

Fluctuations de fréquence compatibles avec :

$$\delta T = 22\ \mathrm{mK}$$



En pratique, en tenant compte de la résolution en fréquence et de la dérive éventuelle de l’oscillateur :

$$\delta T < \pm 2\ \mathrm{mK}$$

3/ Sensibilité du résonateur n’est pas celle attendue ??

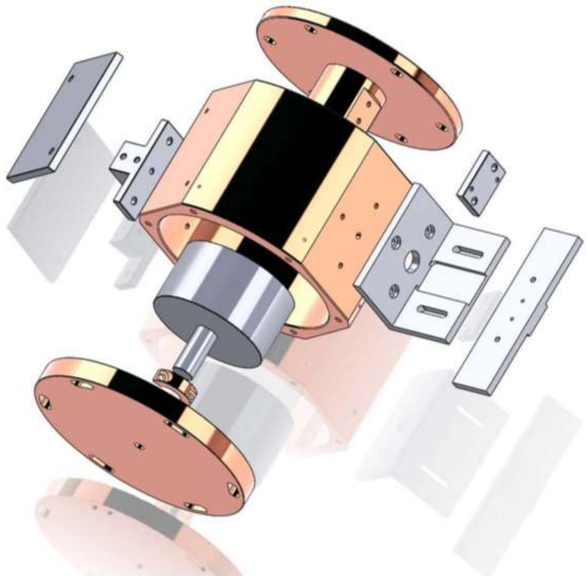
Sensibilité dynamique ???

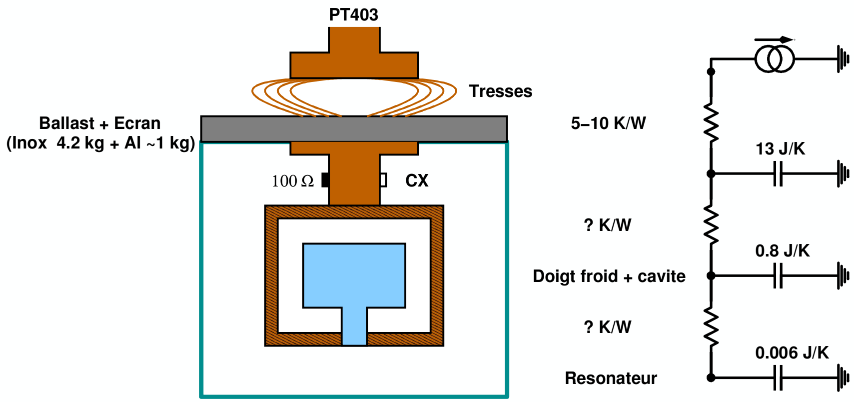
$$\nu(T) - \nu(T_0) = a(T - T_0)^2 + \tilde{a} \times \frac{dT}{dt}$$

- Amélioration de la régulation de température ??

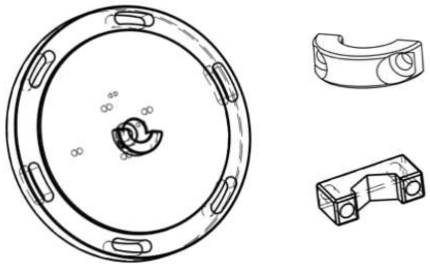
- Sensibilité réelle du résonateur ??

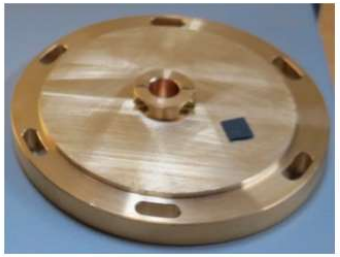
Identification du système thermique

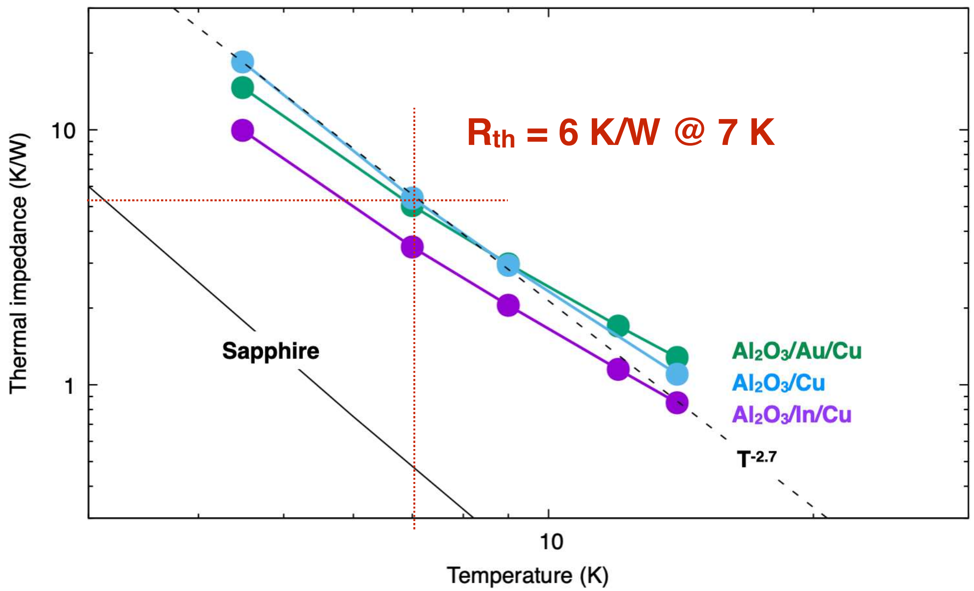




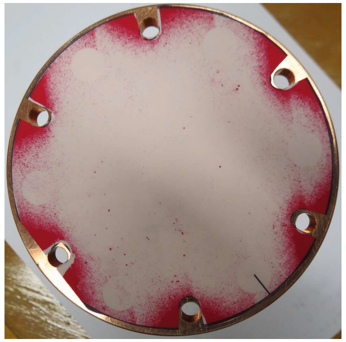
Maintien du résonateur : Résistance thermique



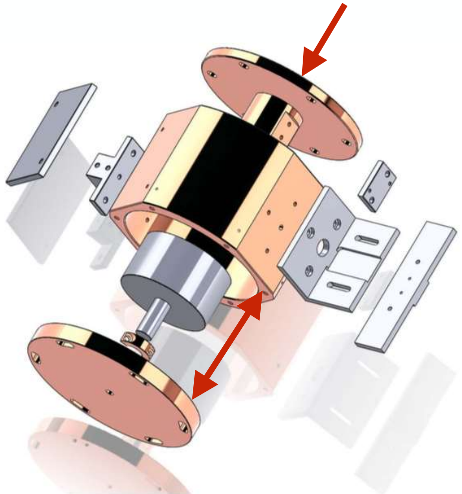


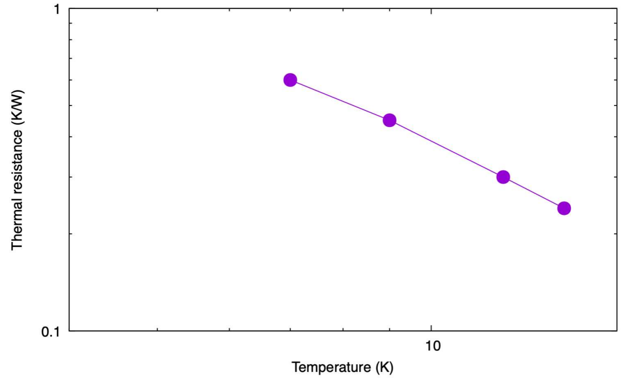


Identification du système thermique



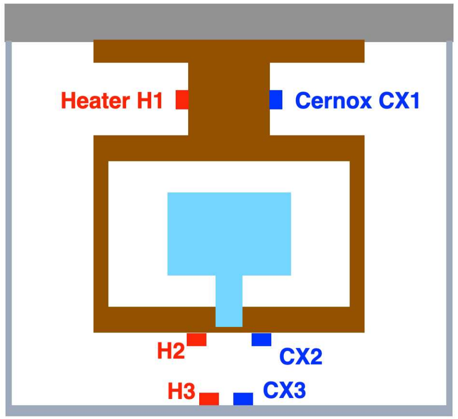
Contact Cavité/Ballast : R_{th} ~ 1 K/W



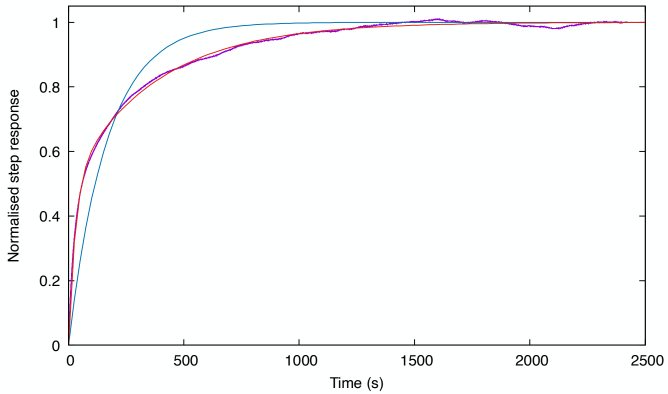


Contact Cavité/Flasque inf. : R_{th} < 1 K/W

Mesures dynamiques



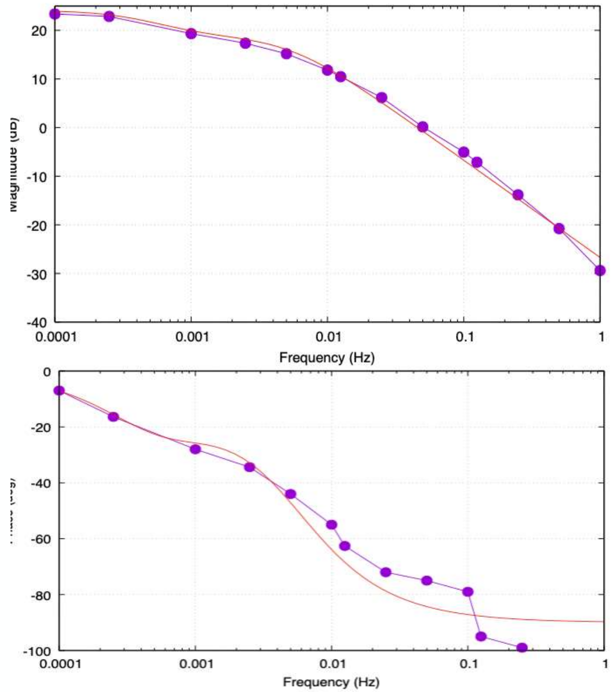
Modulation ou échelon de puissance



Réponse indicielle

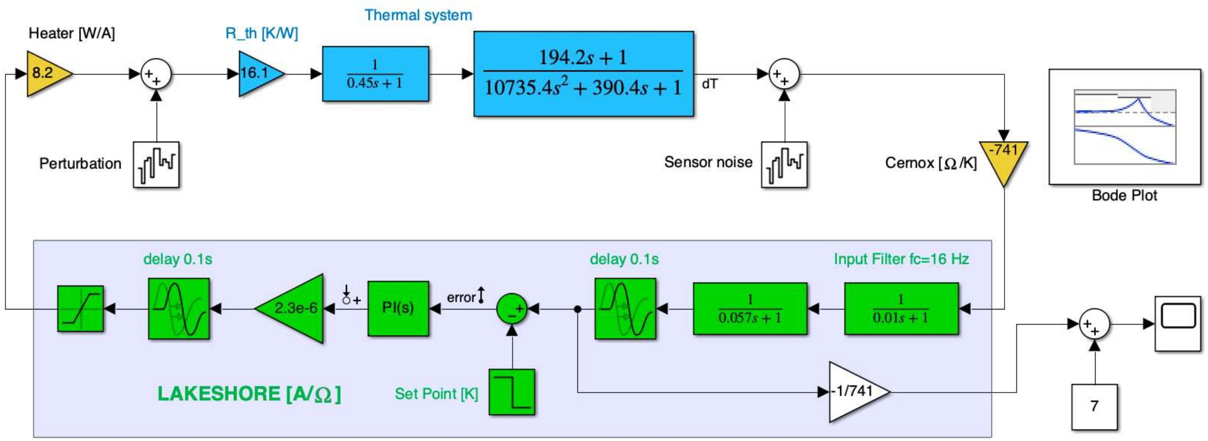
$$H(s) \approx 16.1 \left(\frac{1}{1+0.45s}\right)\left(\frac{1+194.2s}{1+390.4s+10735.4s^2}\right)$$

Réponse harmonique

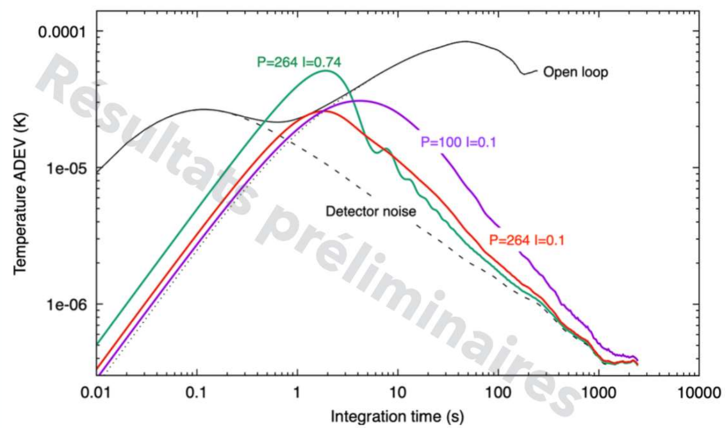


Modèles Simulink/Matlab

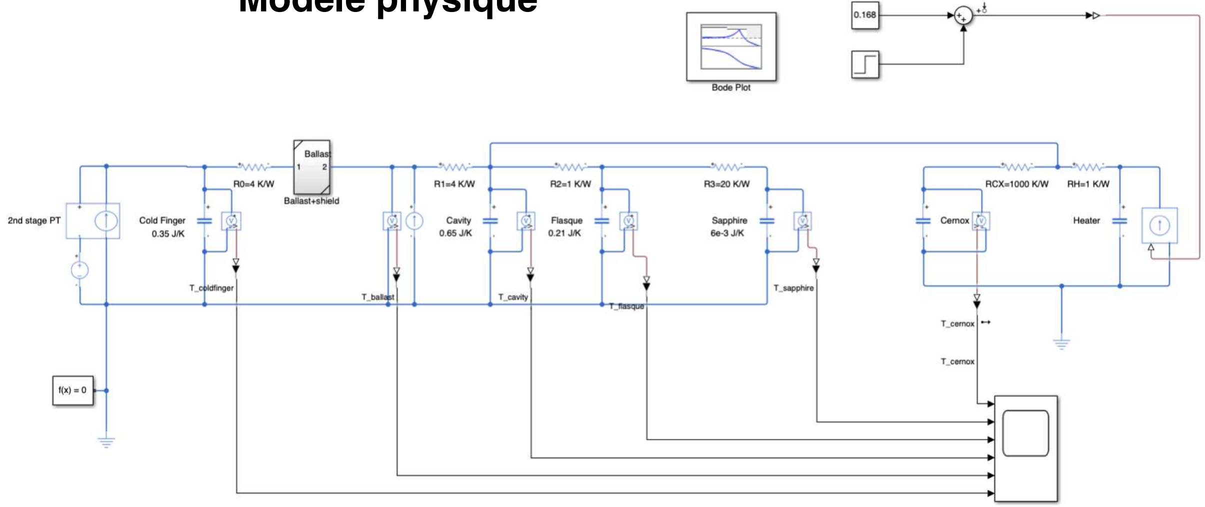
Modèle paramétrique



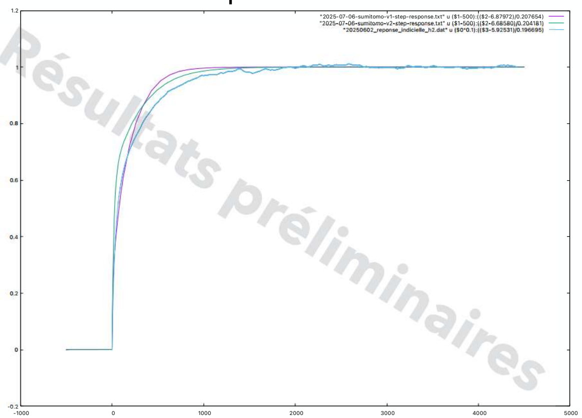
ADEV de la température



Modèle physique



réponse indicielle



Sensibilité réelle du résonateur ??

A. Ballato, *Static and Dynamic Behavior of Quartz Resonators*, 1979.

Use of the static f-T curve in conjunction with the known characteristics of commercial ovens leads to the conclusion that frequency stabilities orders of magnitude better than those observed ought to be possible with AT-cut resonators. The discrepancy is due to the neglect of the dynamic f-T behavior of the crystal

$$\frac{\Delta\nu}{\nu_0} = a(T - T_0) + b(T - T_0)^2 + c(T - T_0)^3 + \tilde{a}\frac{dT}{dt}$$

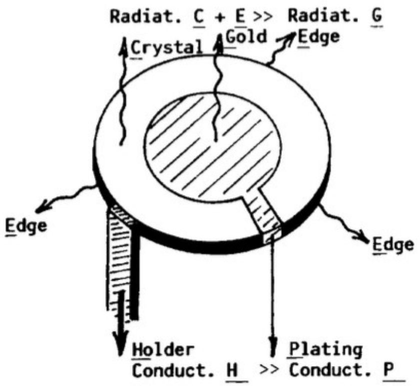


Figure 4

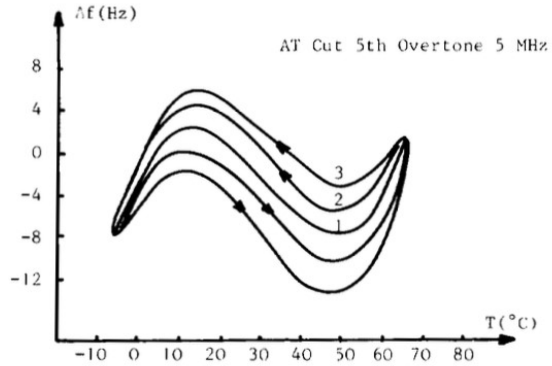


Fig. 3a : Experimental sinusoidal temperature cycling
curve 1 : static f-T behavior
curve 2 : sweep frequency : 2.3 10^{-4} Hz
curve 3 : 4.6 10^{-4} Hz
temperature range ΔT = ± 35°C about 30°C

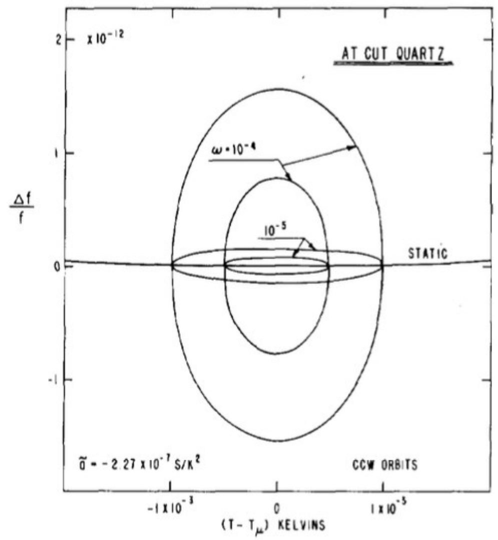


Fig. 8. Elliptical hysteresis orbits for sinusoidal temperature cycling. Temperature sweep ranges 0.5 and 1 millikelvin. Orbital periods are 6.28 × 10^4 and 6.28 × 10^5 s, for $\omega = 10^{-4}$ and 10^{-5}, respectively. It is seen that even diurnal rhythms contribute significantly to frequency instability.

$$\nu(T) - \nu(T_0) = a(T - T_0)^2 + \tilde{a} \times \frac{dT}{dt}$$

Sensibilité dynamique ???

Kovarich (UWA) 2005

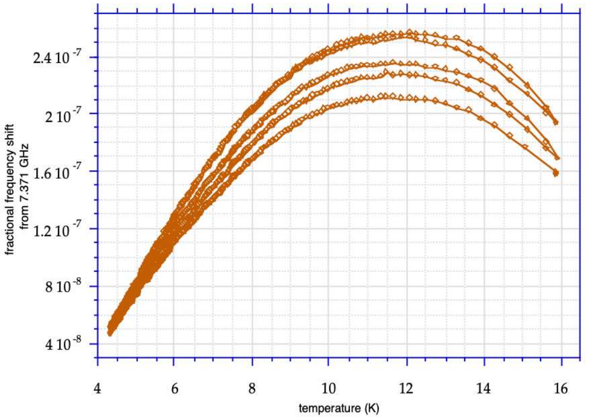
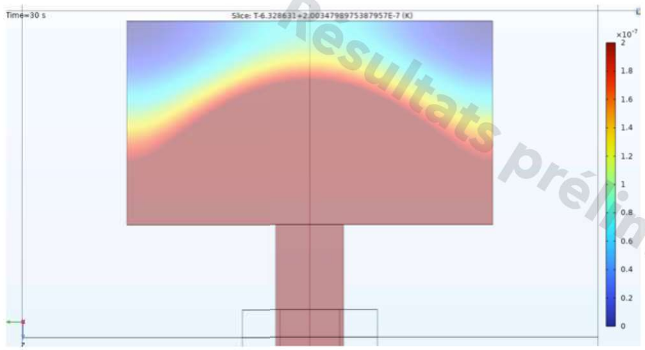
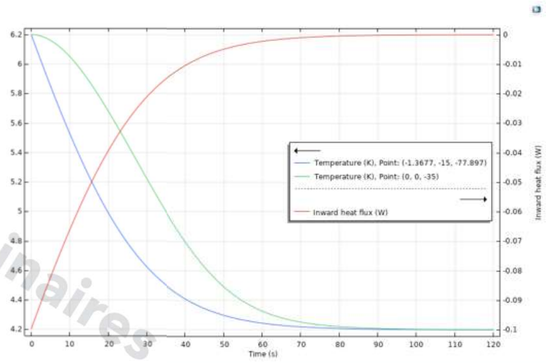


Figure 32) Frequency versus temperature function for a CSDR mode at 7.371 GHz , obtained over 17 hours. The looseness between the sapphire spindle and the cups that support it causes the following: Hysteresis due to poor thermal contact and curve distortion due to frequency drift caused by mechanical instability of the CSDR.

Modèle COMSOL G. Le Tetu (FEMTO-ST)

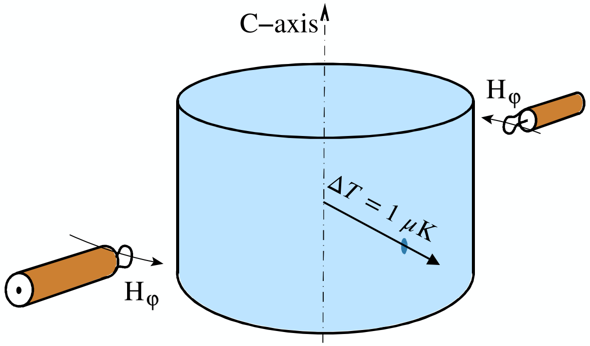


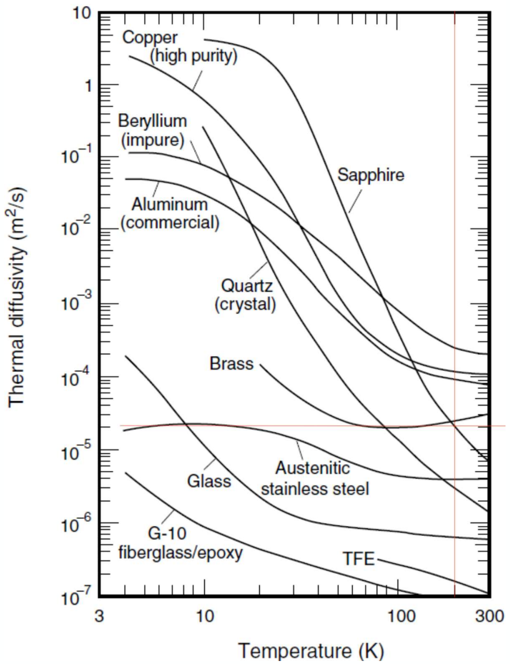


Modèle Mode Matching
perturbation au 1er ordre

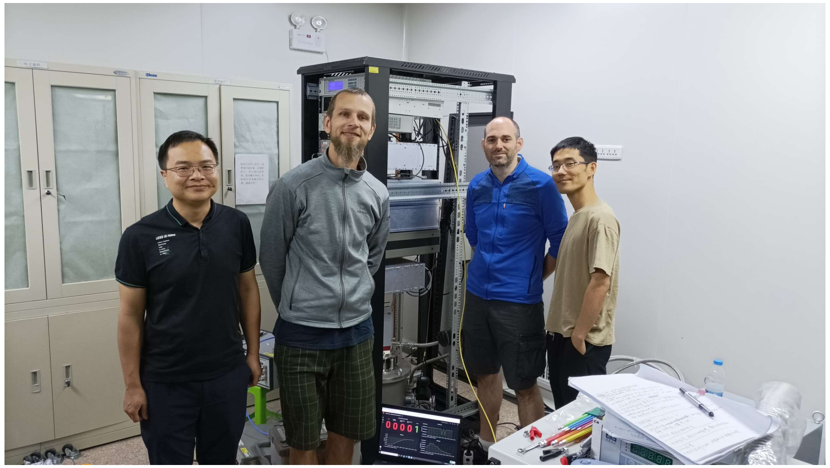
1 μK de gradient radial
+
T0 + 2 mK

—> df/f = 10^{-15}





NTSC Xian PRC June 2023



NPL Teddington April 2022

Merci de votre attention

USNO Washington January 2024