Assemblée générale FIRST-TF
Besançon – 04 et 05 octobre 2022

Vers une technologie CSO de 3eme génération (CSO 3G)

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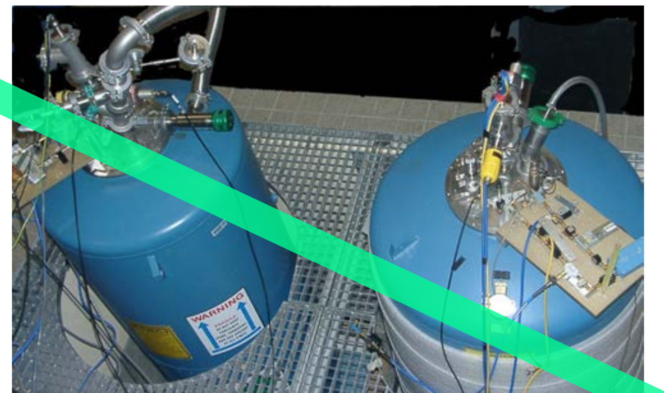
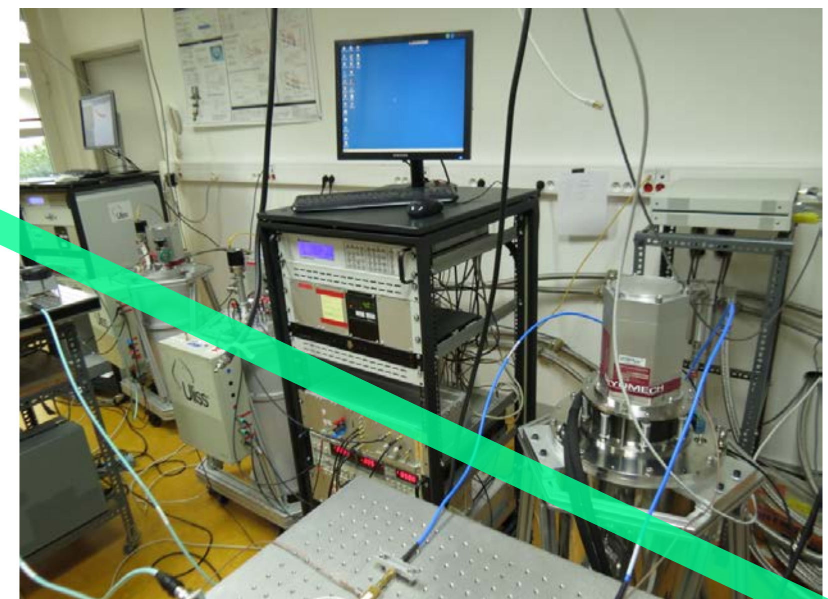
- Rappels sur la technologie ULISS-2G
- Objectifs du projet
- Etat d'avancement

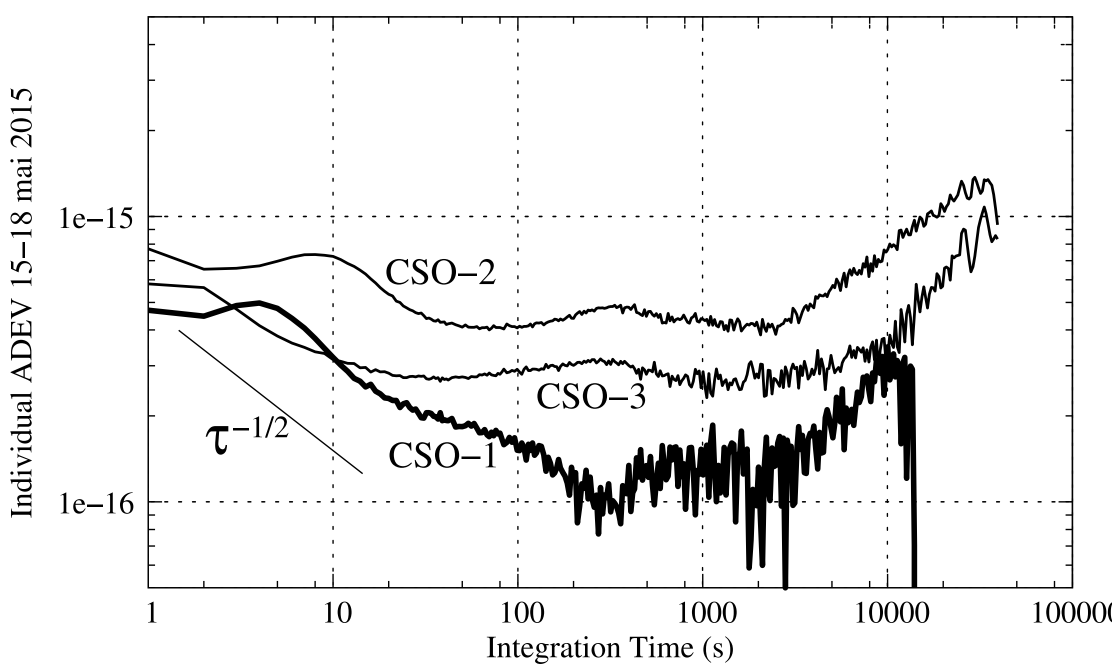
Cryogenic Sapphire Oscillator is only technology to provide a relative frequency stability better than 1×10^{-15} for integration times ranging from 1 s to 10^{4} s

2004
First LHe CSO
at FEMTO-ST

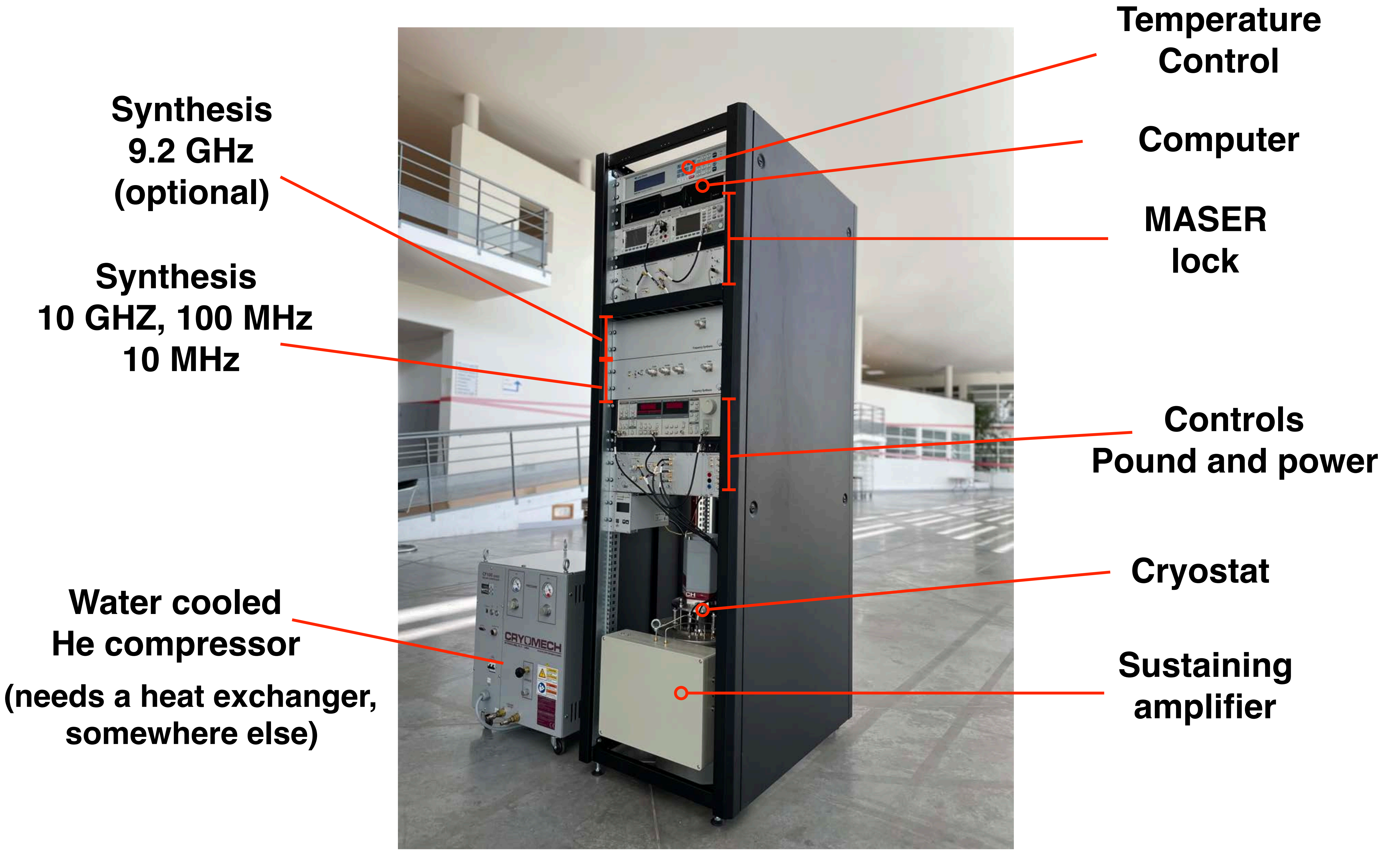


2012-2014
OSCILLATOR-IMP
3 CSOs fully operational





2017
3 kW CSO

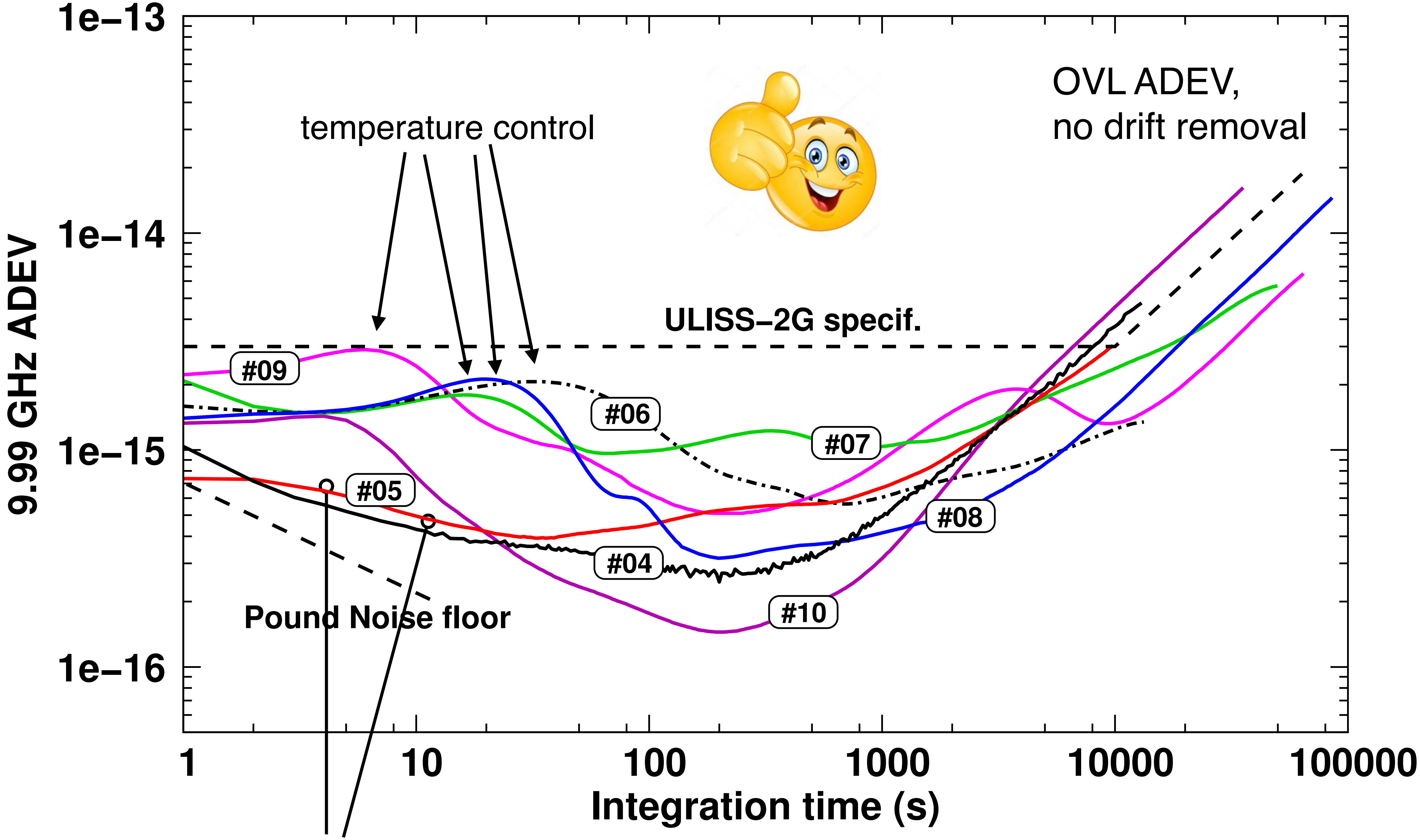


https://www.femto-engineering.fr/realisation/oscillateur-cryogenique-ultrastable-uliss/

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

#	Nickname	Power	first operation	status
000	ELISA	6 kW	June 2009	Prototype
001	MARMOTTE	6 kW	Oct. 2010	OSCILLATOR IMP Reference
002	ULISS	6 kW	Nov. 2011	OSCILLATOR IMP Reference, Transportable unit
003	ABSOLUT	7 kW	May 2014	OSCILLATOR IMP Reference
004	ULISS-2G 004	3 kW	June 2015	Prototype, principle demonstration
005	ULISS-2G 005	3 kW	Dec. 2017	Commercial product (delivered) USNO
006	ULISS-2G 006	3 kW	Nov. 2018	Commercial product (delivered) USNO
007	ULISS-2G 007	3 kW	June 2019	Commercial product (delivered) USNO
008	ULISS-2G 008	3 kW	Dec. 2020	Commercial product (delivered) NTSC
009	ULISS-2G 009	3 kW	April 2021	Commercial product (delivered) NPL
010	ULISS-2G 010	3 kW	March 2022	Commercial product (delivered) INRIM

ULISS 2G – 7 units implemented

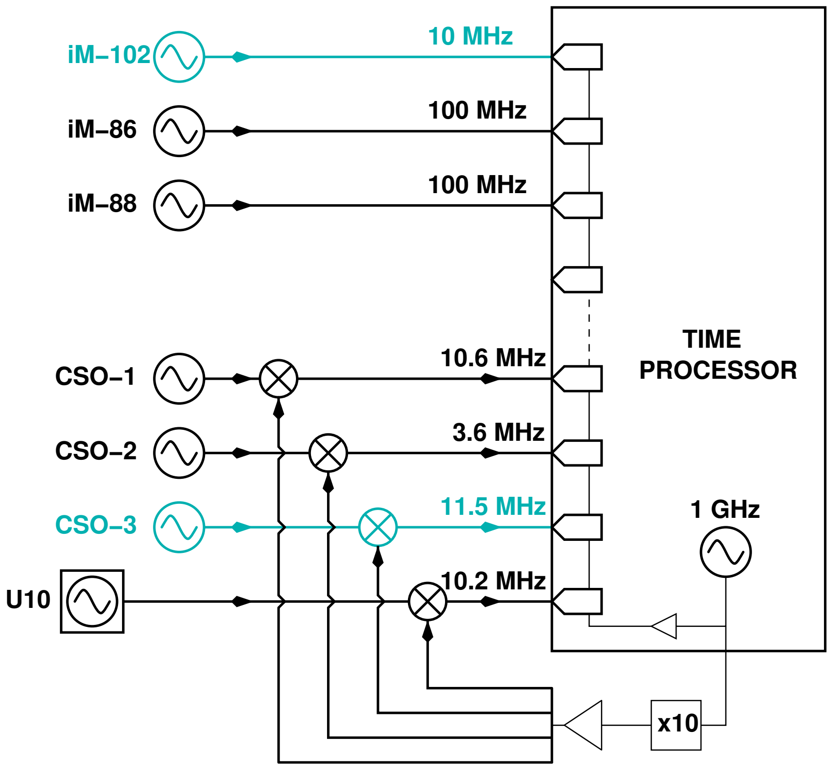


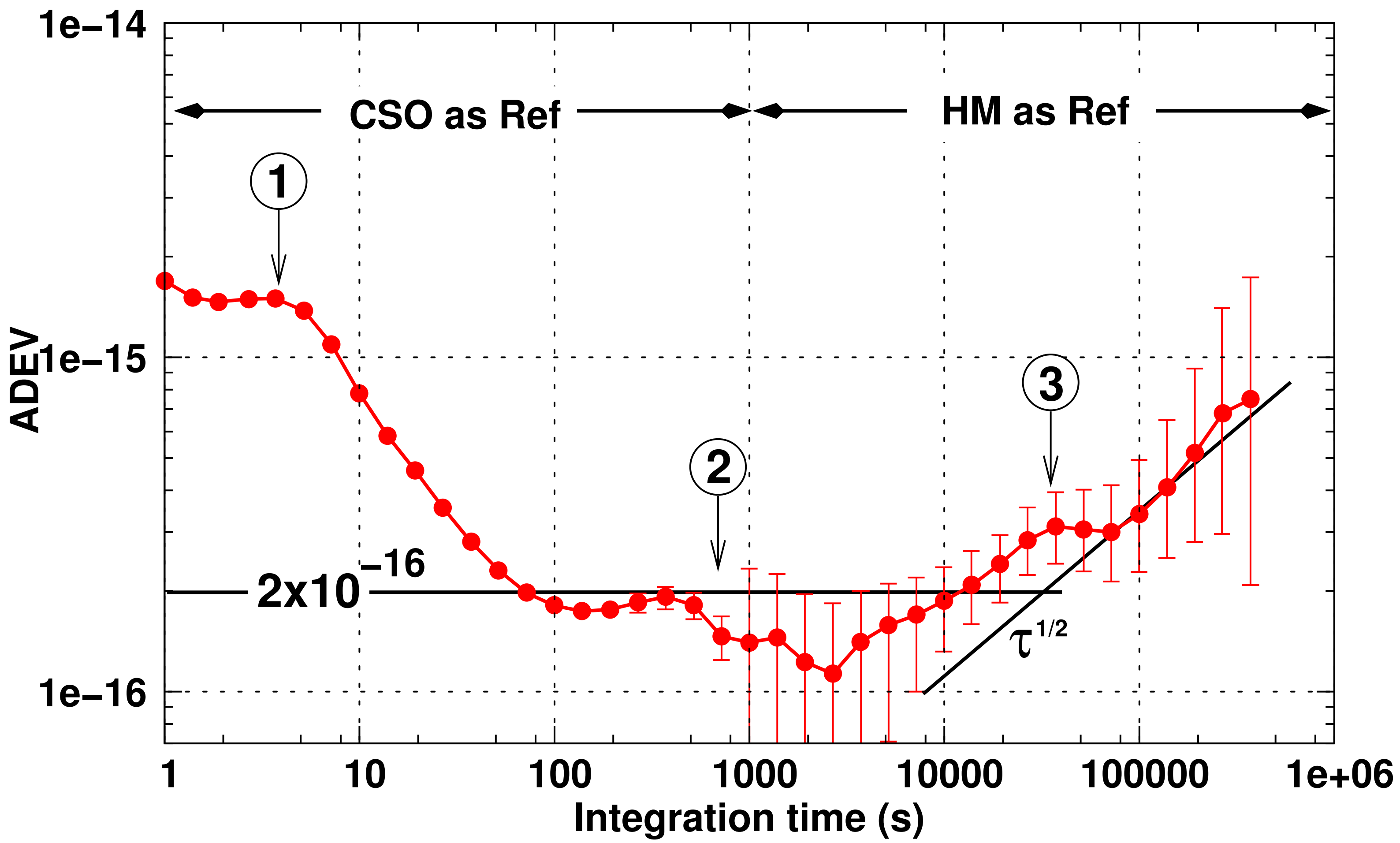
lower turning point (≈ 5 K)
(regular TP is 6-7.5 K)

#4 : first ULISS-2G prototype
#10 : newly implemented

ULISS 2G 010

juillet 2022

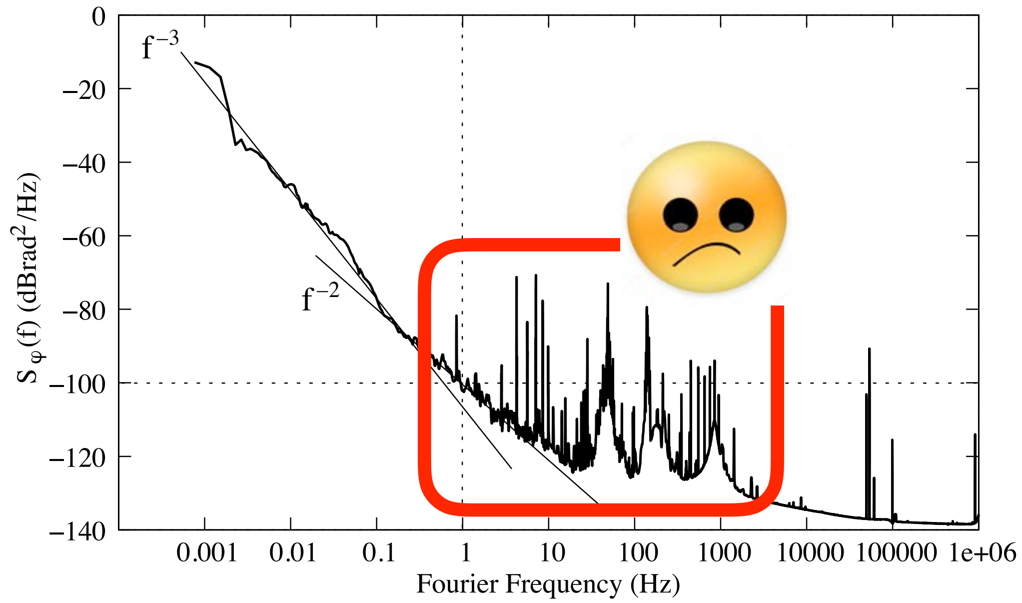




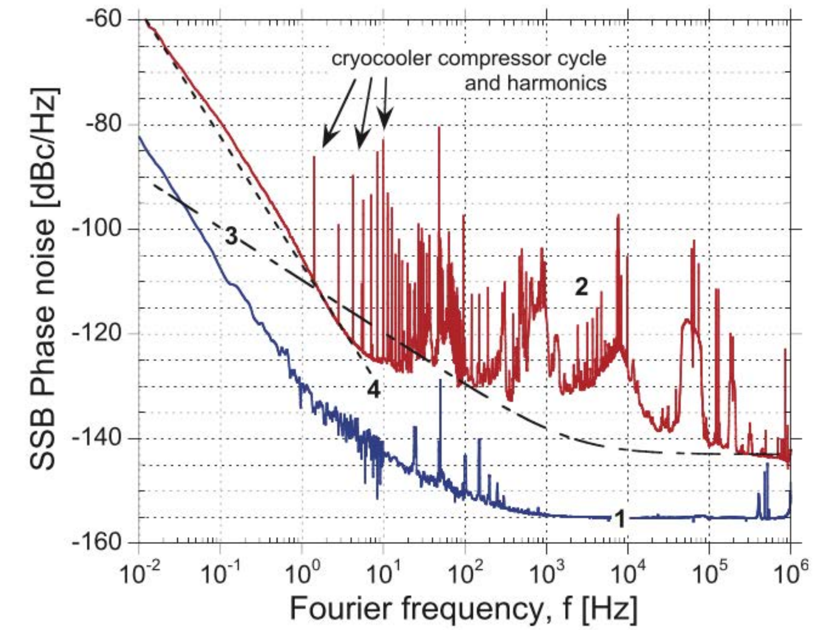
Objectifs du projet

1/ Amélioration du spectre de bruit de phase

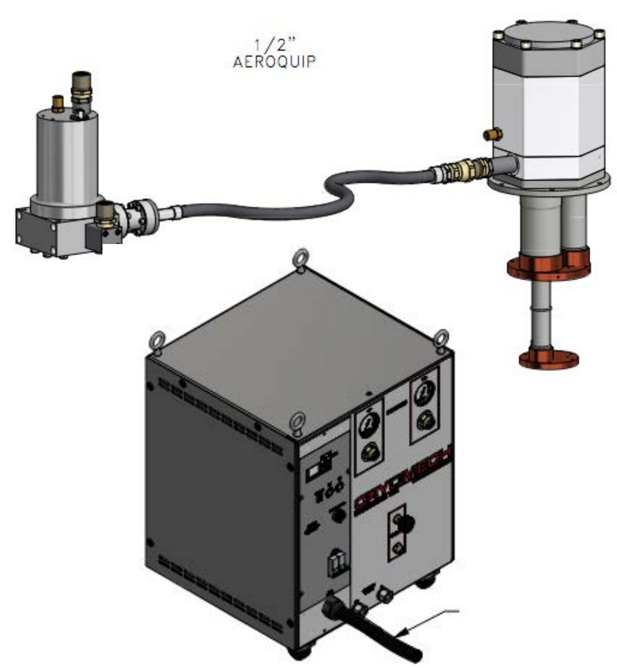
ULISS 2G Phase noise



CryoSapphire Phase noise



2/ Alternatives pour ULISS 2G Cryocooler



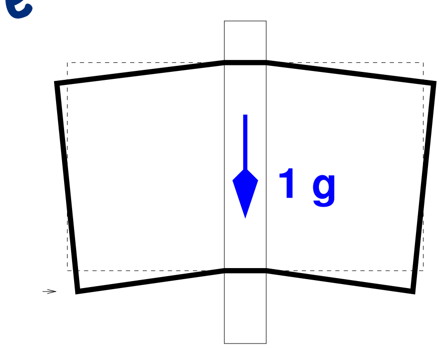
Only one supplier :
3kW PT-403 Cryomech
~ 220 mW @ 4 K

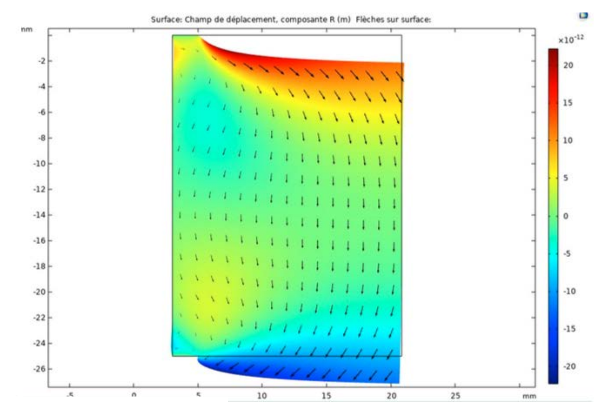
Autres possibilités :

- **Cryo GM de Sumitomo (J)**
- **Cryo PT de Transmit (Ge)**

Résonateur : Sensibilité aux vibrations

1/ Déformation mécanique





$$\frac{1}{\gamma_z}\frac{\Delta\nu}{\nu_0}\Big|_{geo} = 2.5 \times 10^{-10}\ /g$$

2/ Effet « photoélastique »

Symétrie C3m (sapphire)
6 coefficients indépendants
Du tenseur dielectrico-elastic

$$\begin{pmatrix} \varepsilon_{\parallel}(0) \\ \varepsilon_{\parallel}(0) \\ \varepsilon_{\perp}(0) \\ \\ \\ \\ \end{pmatrix} + \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & 0 & 0 \\ p_{12} & p_{22} & p_{13} & -p_{14} & 0 & 0 \\ p_{13} & p_{13} & p_{33} & 0 & 0 & 0 \\ p_{14} & -p_{14} & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & p_{14} \\ 0 & 0 & 0 & 0 & p_{14} & 1/2(p_{11}-p_{12}) \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{pmatrix}$$

?

Mesures

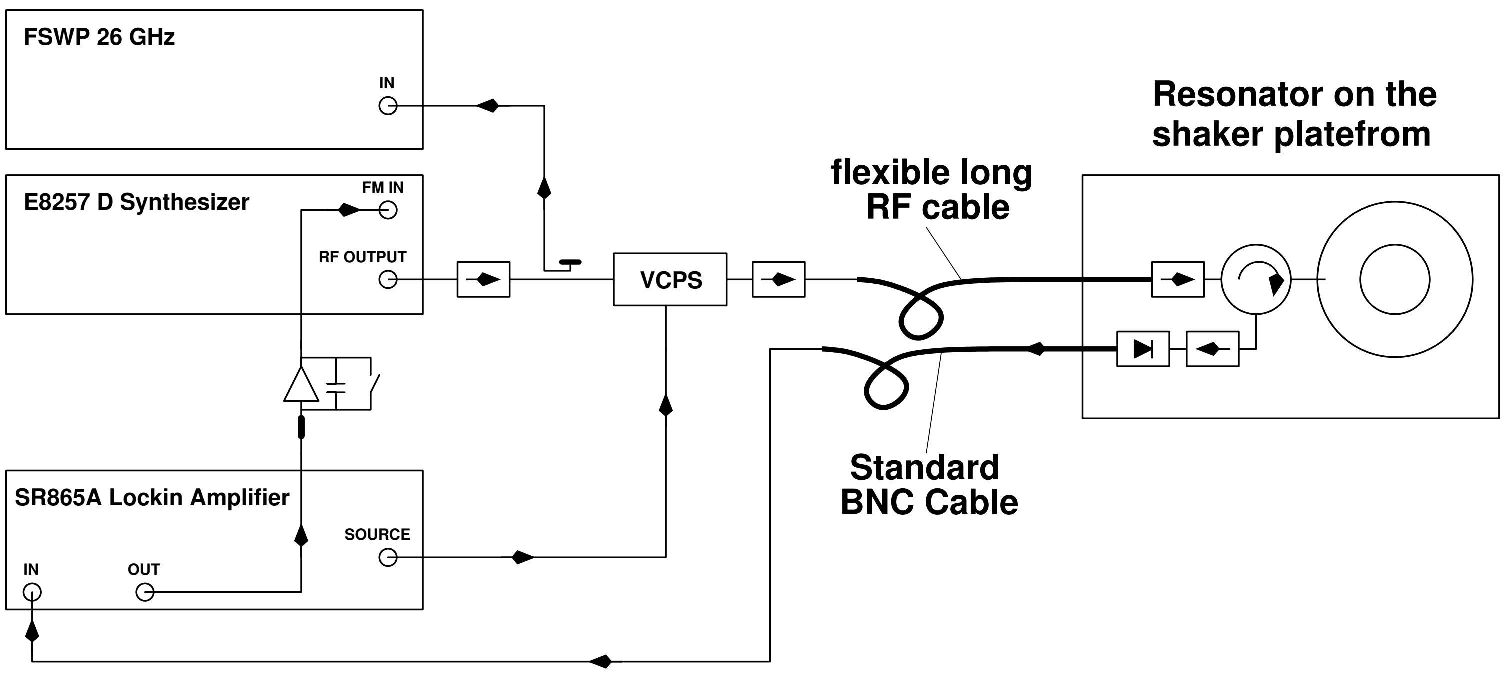
Modèle

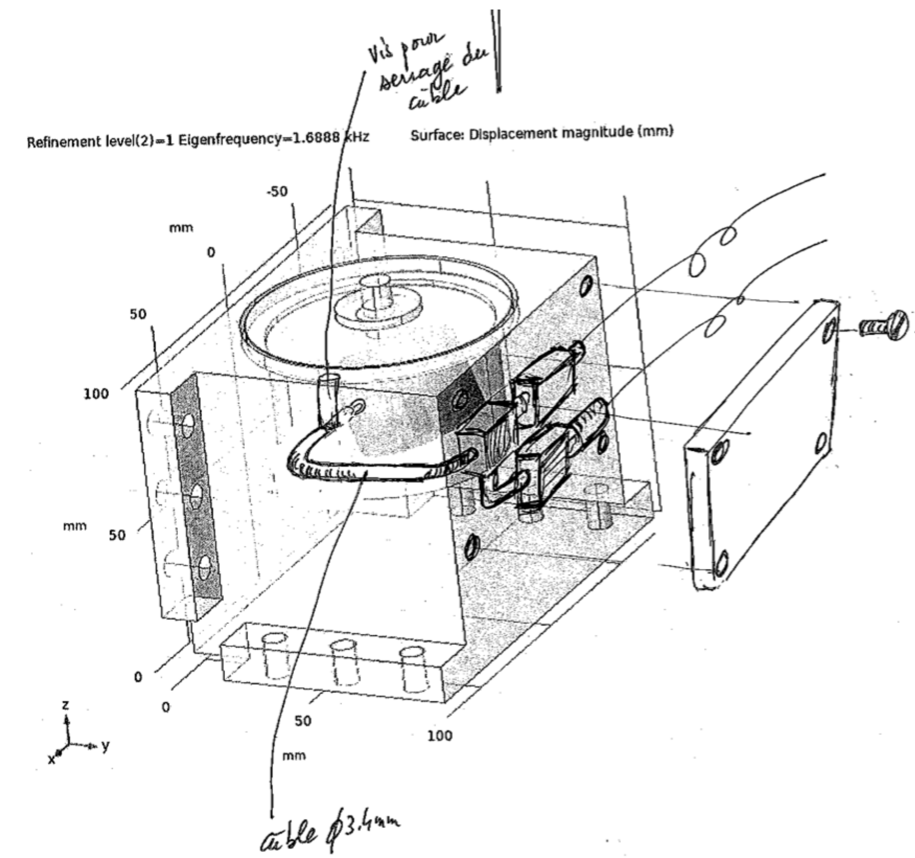
Samuel Margeron FEMTO-ST
Celine DUPONT UMR 6303 CNRS
Université de Bourgogne

?

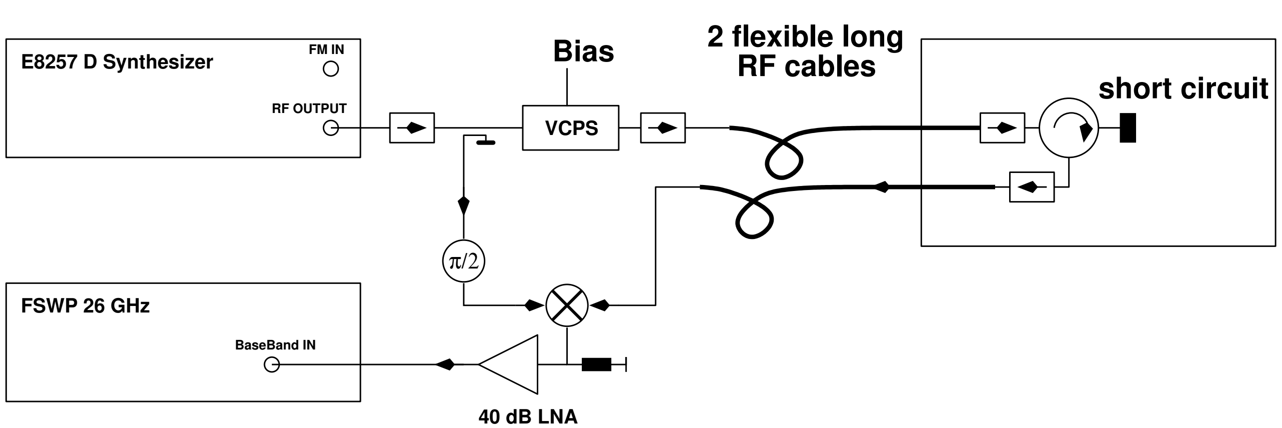
Nouvelle géométrie

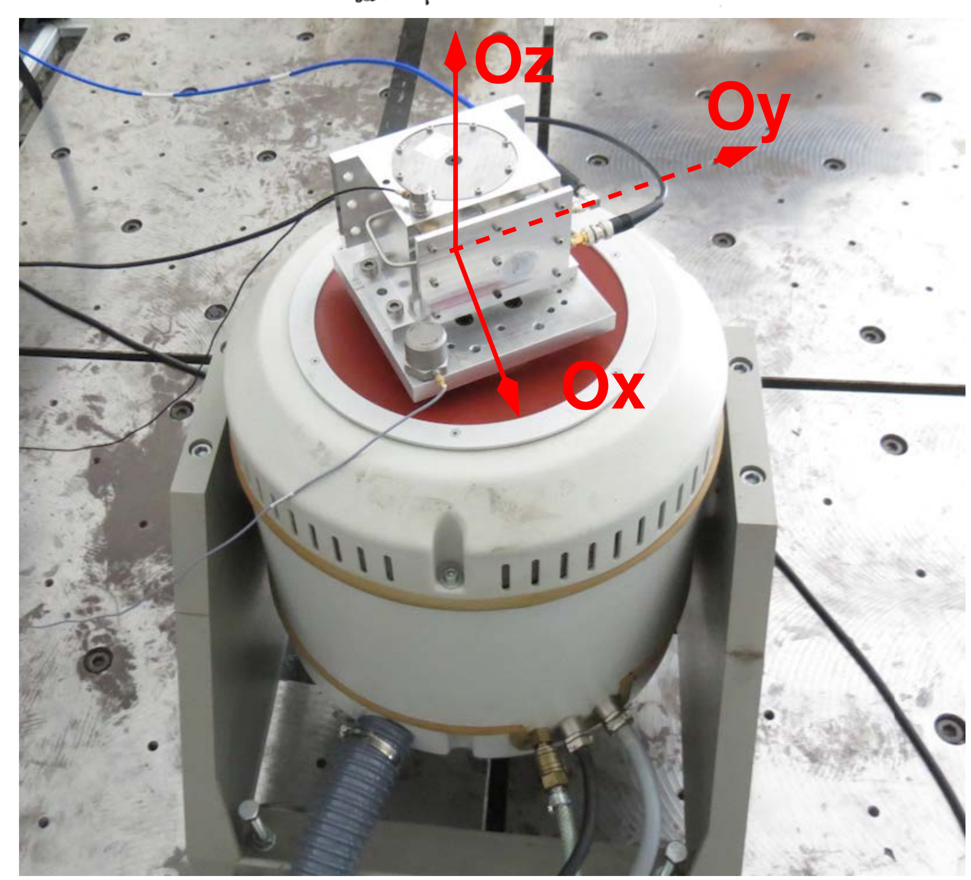
Mesure de la Sensibilité aux vibrations





Contribution des câbles :





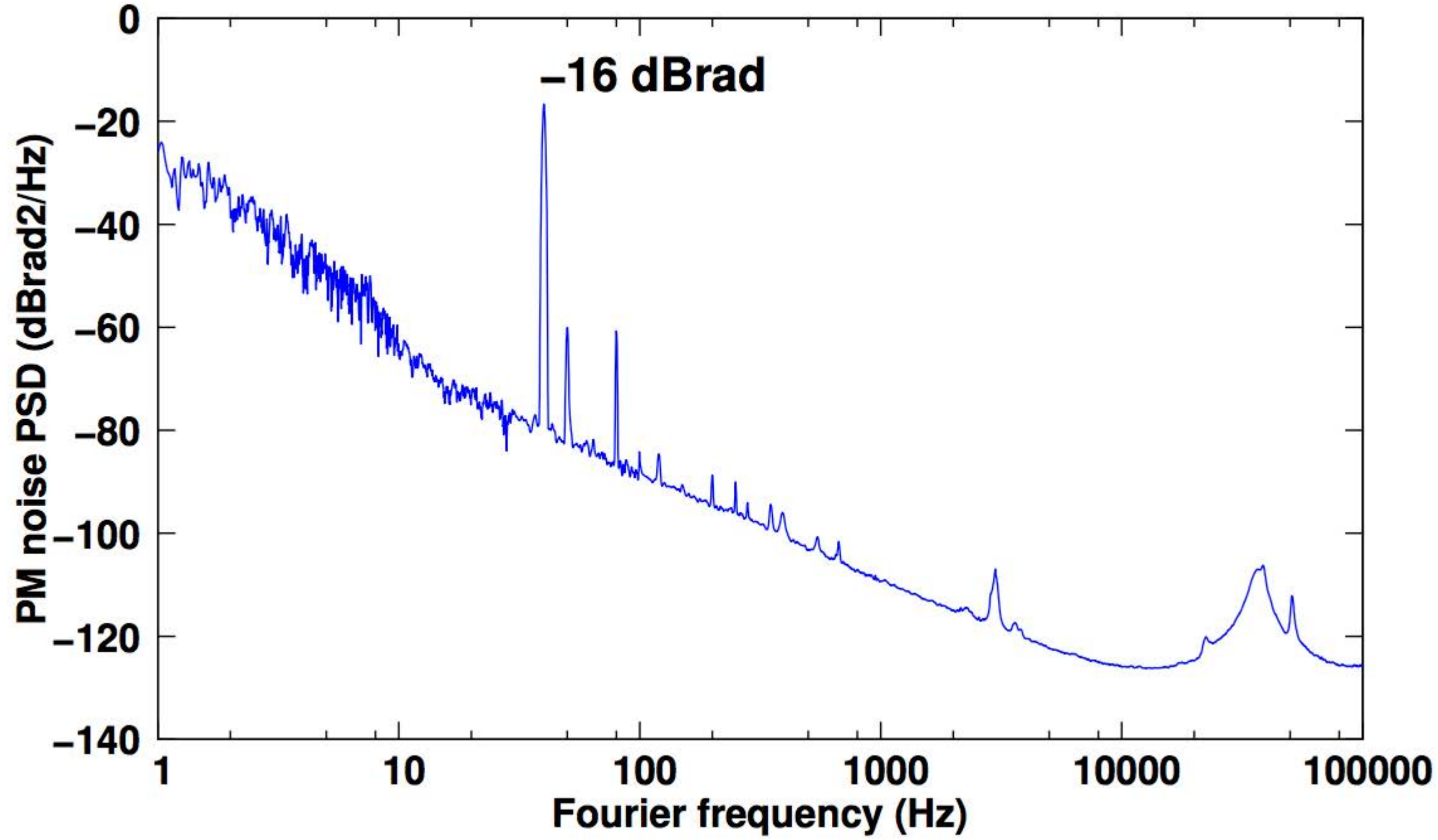


Figure 9: *E8257 PM noise PSD with* $\gamma_z = 1g$*-pic at 40 Hz.*

$$\Gamma_z = \frac{f_m}{\nu_0} \frac{\sqrt{S_\varphi(f_m)}}{\gamma_{z|rms}} = 9.2 \times 10^{-10}\ \mathrm{g}^{-1}$$

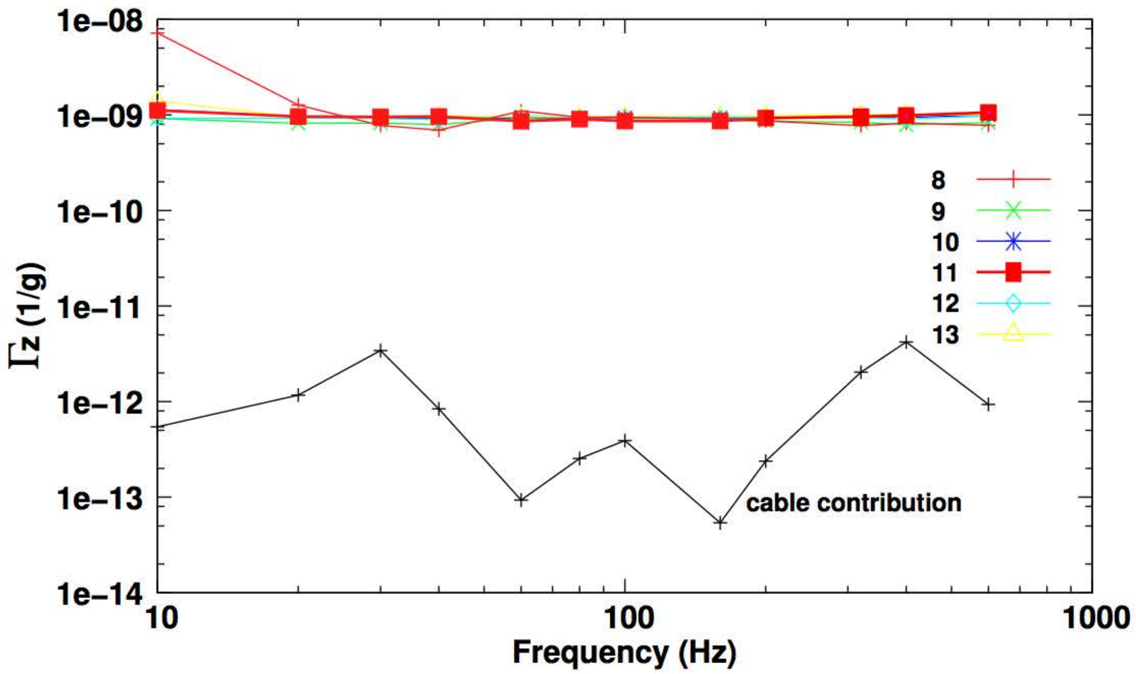


Figure 12: *Axial g-sensitivity vs azimutal number.*

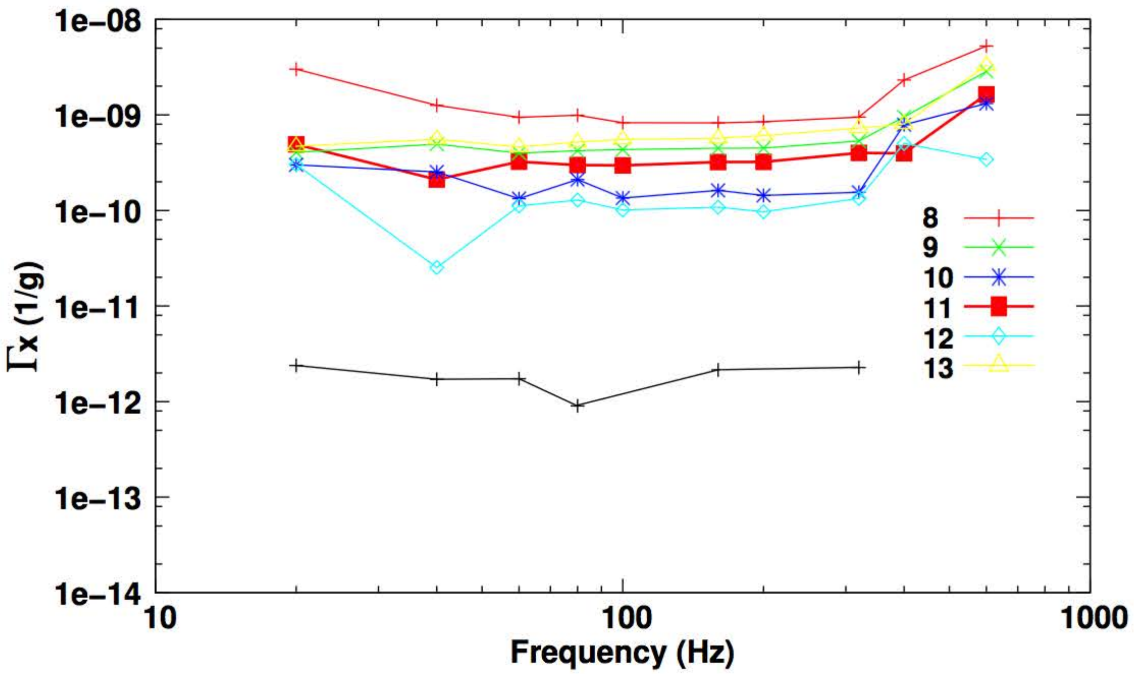


Figure 13: *OX g-sensitivity vs azimutal number.*

Table 2: Measured acceleration sensitivities

m	Γ_Z $(\times 10^{-9}/\mathrm{g})$	Γ_X $(\times 10^{-10}/\mathrm{g})$
8	1.0	8.0
9	1.0	4.5
10	1.0	1.5
11	1.0	3.1
12	1.0	1.0
13	1.0	5.0

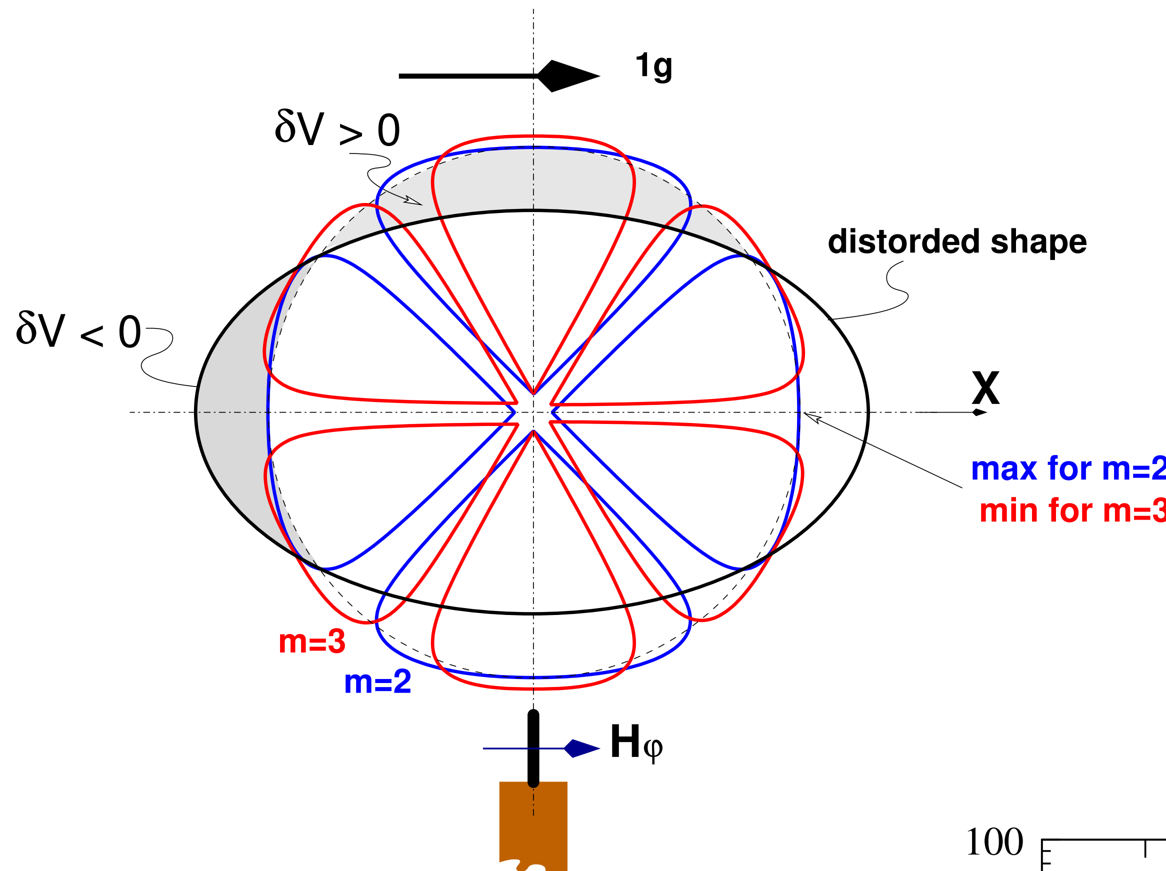
$\Gamma_z = 2.4 \times 10^{-9}/\mathrm{g}$ A. N. Luiten, PhD thesis, U.W.A., 1995.

$|\Gamma| \leq 5 \times 10^{-10}/\mathrm{g}$ P. Stockwell et. al. in Proc. IFCS 2001.

$\Gamma_z = 3.2 \times 10^{-10}/\mathrm{g}$ M. Oxborrow et. al. in Proc. EFTF 2008.

$$|\Gamma| \sim 1 \times 10^{-9}/\mathrm{g} \quad \text{et} \quad \frac{\Delta\nu}{\nu} \leq 10^{-15} \quad \rightarrow \text{le } \mu g \text{ est requis !}$$

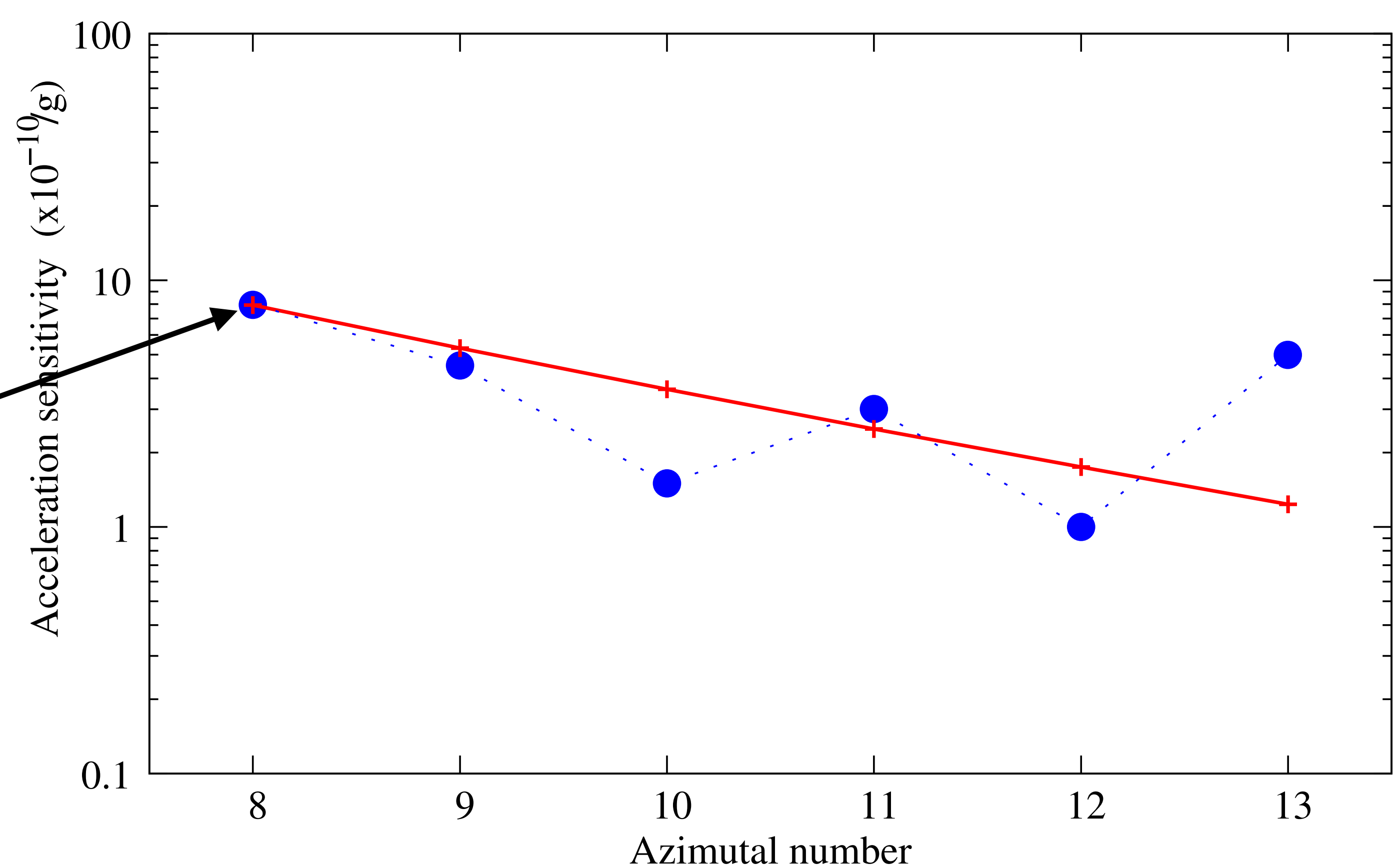
Sensibilité transverse dépend de m ?
Tentative d'explication



champs EM calculés avec Mode Matching

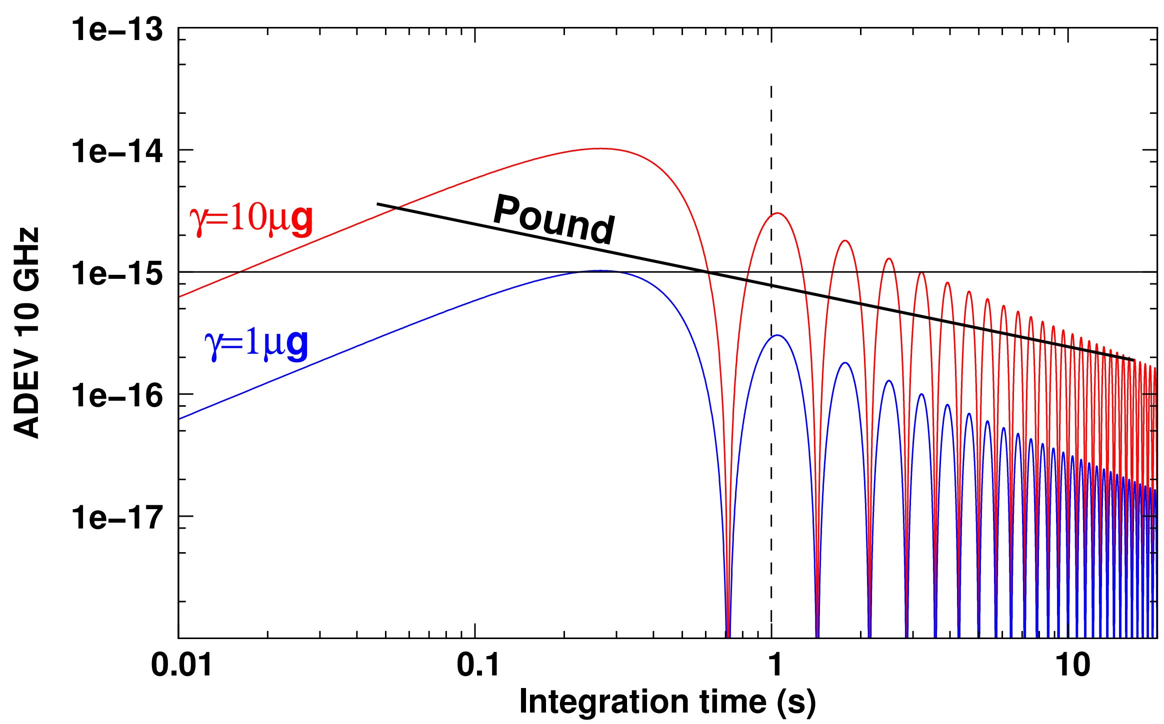
$$\frac{\Delta\nu}{\nu_0} = \frac{\int_{\delta V} \mathbf{E}\left([\varepsilon]-1\right)\mathbf{E}^* dv}{\int_V \left(\mu_0 \mathbf{H}^2 + \varepsilon_0 \mathbf{E}[\varepsilon]\mathbf{E}^*\right) dv}$$

Mise à l'échelle pour être compatible avec mesure pour m=8



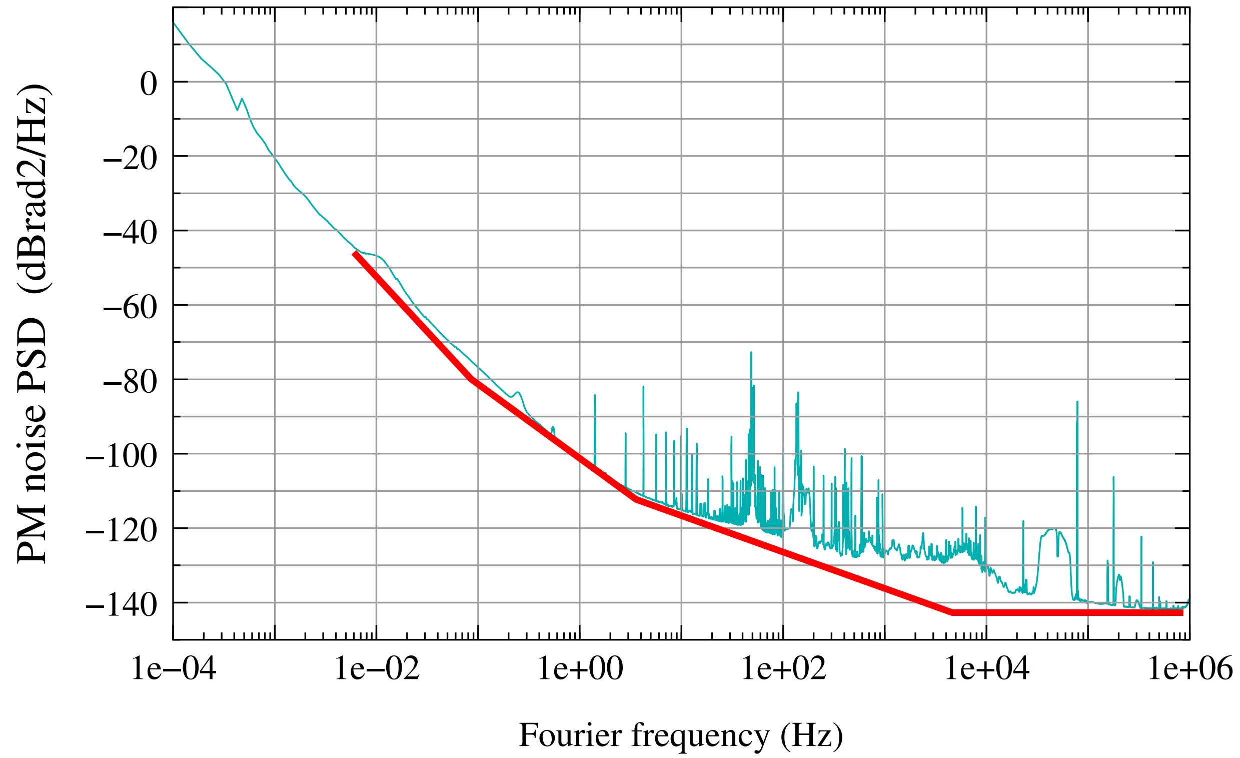
Accélération acceptable ? Quel critère ?

ADEV ?



1 *μ*g -> 13 nm
@ 1.4 Hz

Phase Noise



Gagner
au moins 20 dB !!

Atténuation des vibrations générées par un cryogénérateur :
Problème pour de nombreuses applications scientifiques

- Microscopie
- Interferométrie optique (GW detection …)
- Ions piégés (horloge optique, quantum computing)
- Spatial
- …

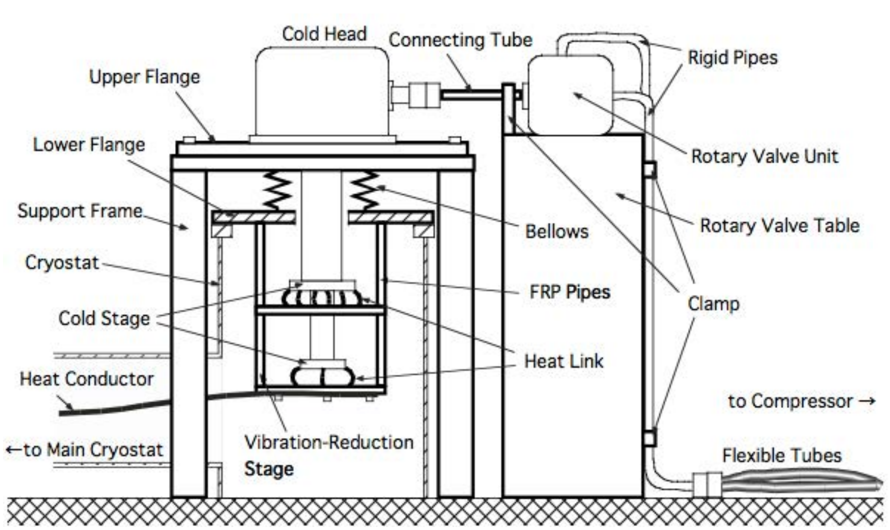
-> biblio très fournie decrivant ≠ réalisations très spécifiques: 3 « concepts »

T. Tomaru

Cryocoolers

13, p. 645-702 (2004)

10.1007/0-387-27533-9_86



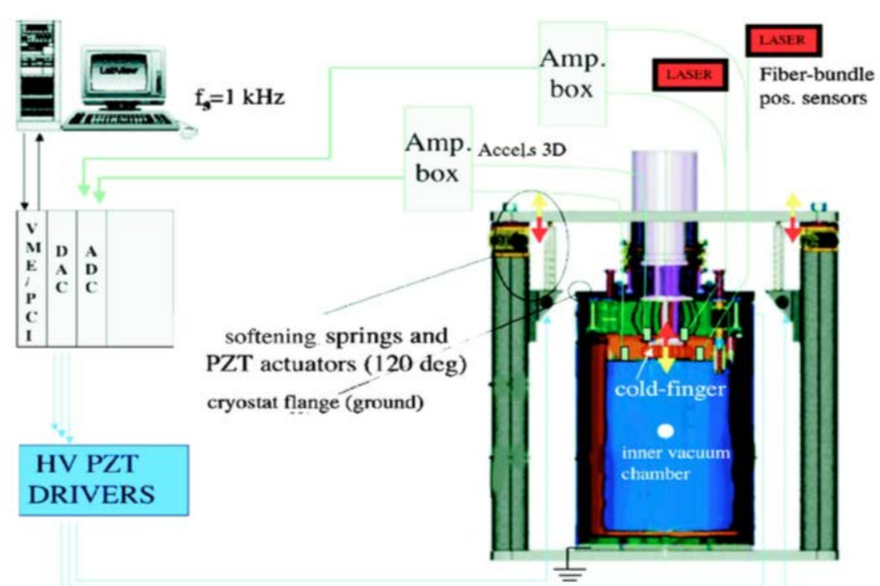
Solutions passives
lien thermiques flexibles
Structure support rigide

S. Caparrelli

Review of Scientific Instruments

77, 095102 (2006)

https://doi.org/10.1063/1.2349609



Correction active avec détecteurs
et actuateurs piezos

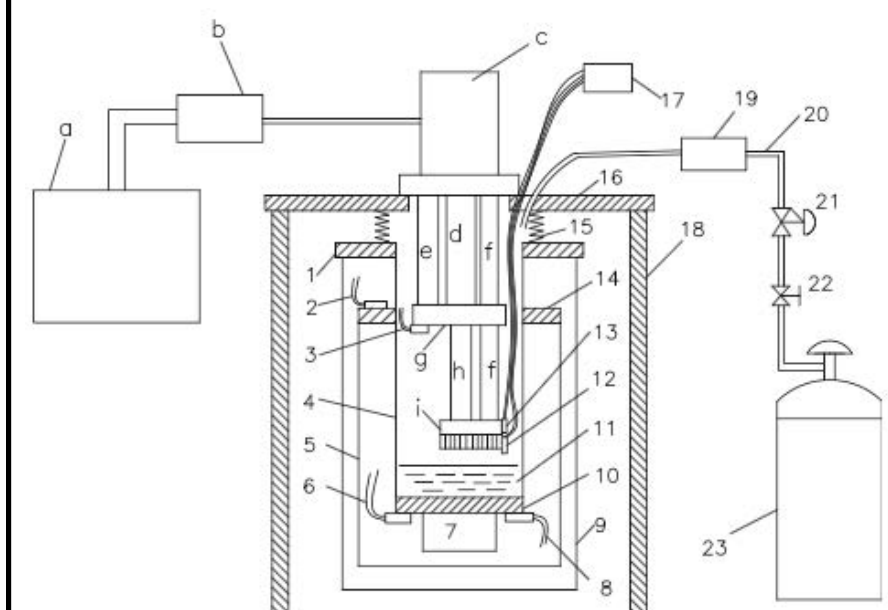
Complexe : mise en oeuvre et ajustement
Efficacité suivant 3 axes pas démontrée

C. Wang

Cryogenics

50, 5, p. 336-341 (2010)

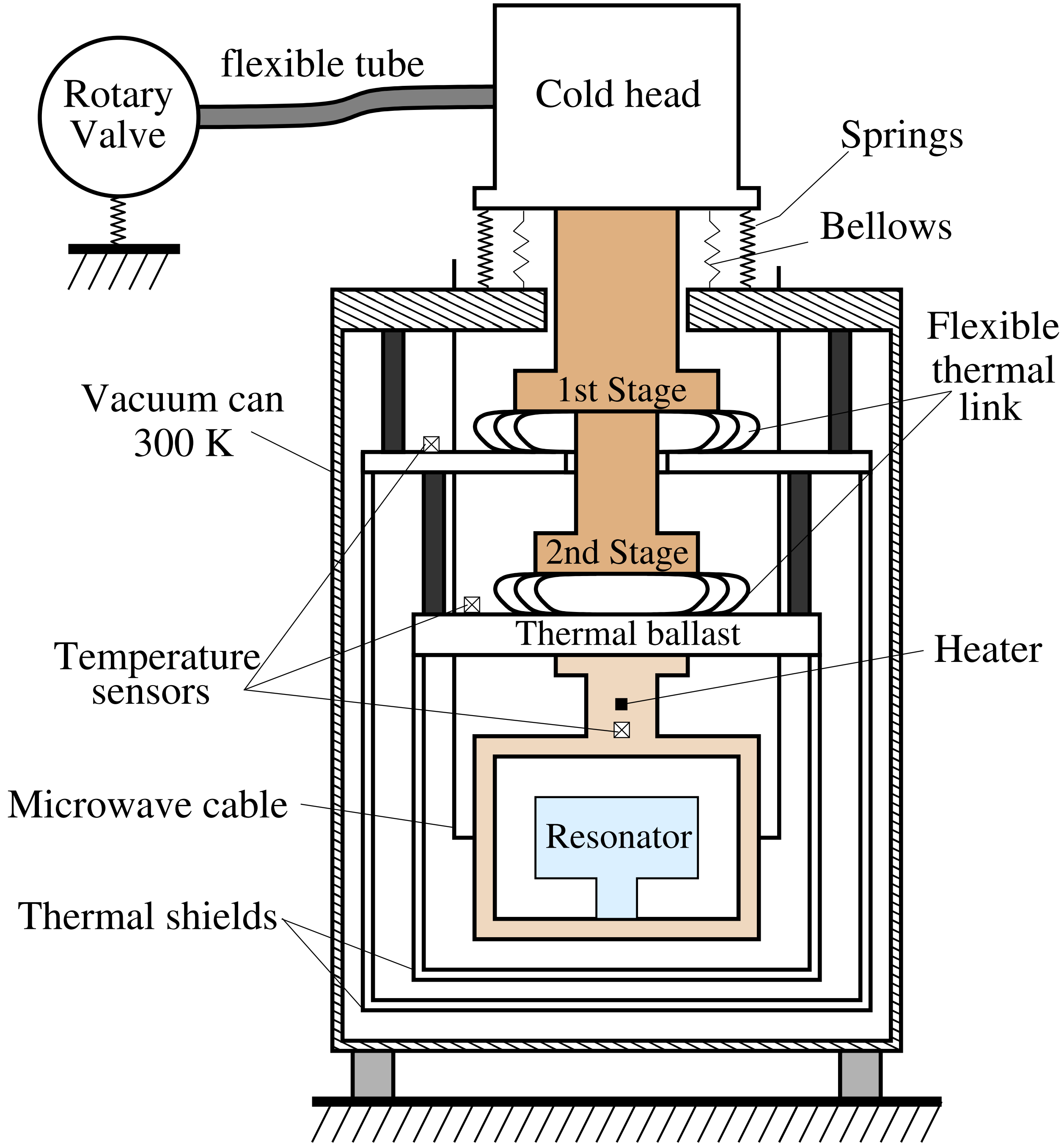
10.1016/j.cryogenics.2010.01.003

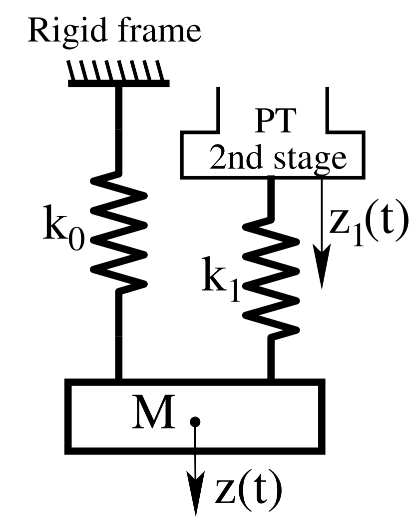


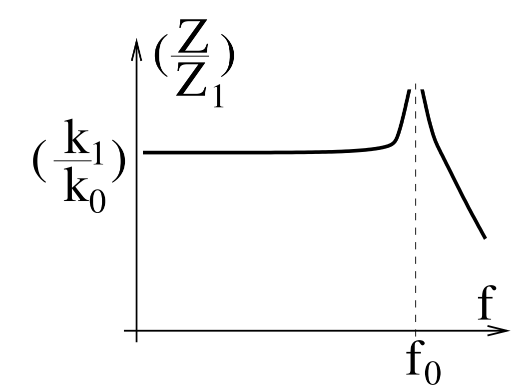
Interface : équilibre liquide/vapeur He
Pas de contact mécanique
entre expérience et doigt froid

Complexe : mise en oeuvre et ajustement
Pas compatible avec P_{elec} < 4 kW

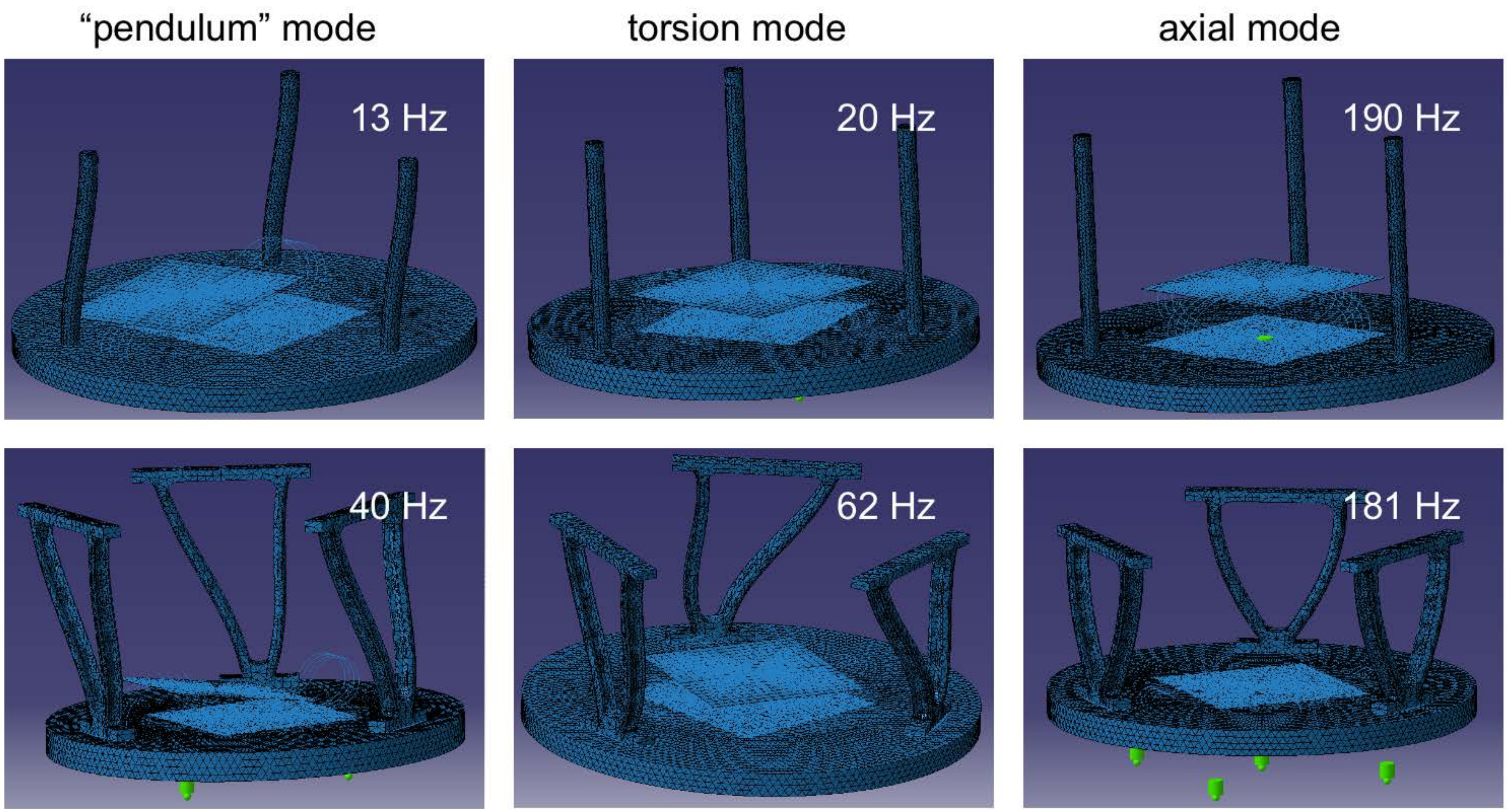
ULISS-2G : Configuration retenue







Optimisation: compromis entre T mini et isolation des vibrations

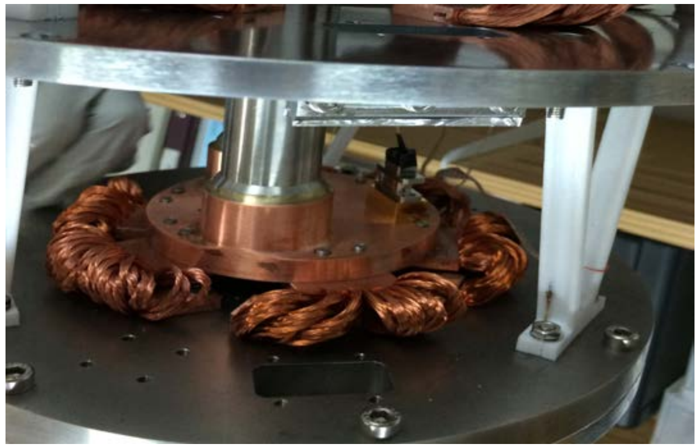


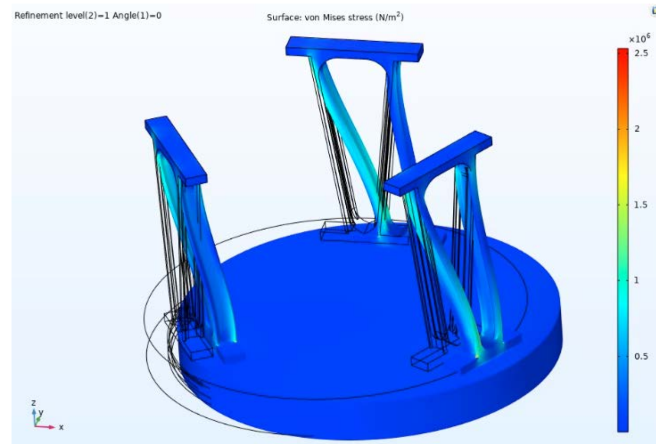
Mechanical damping in the axial and transverse directions.

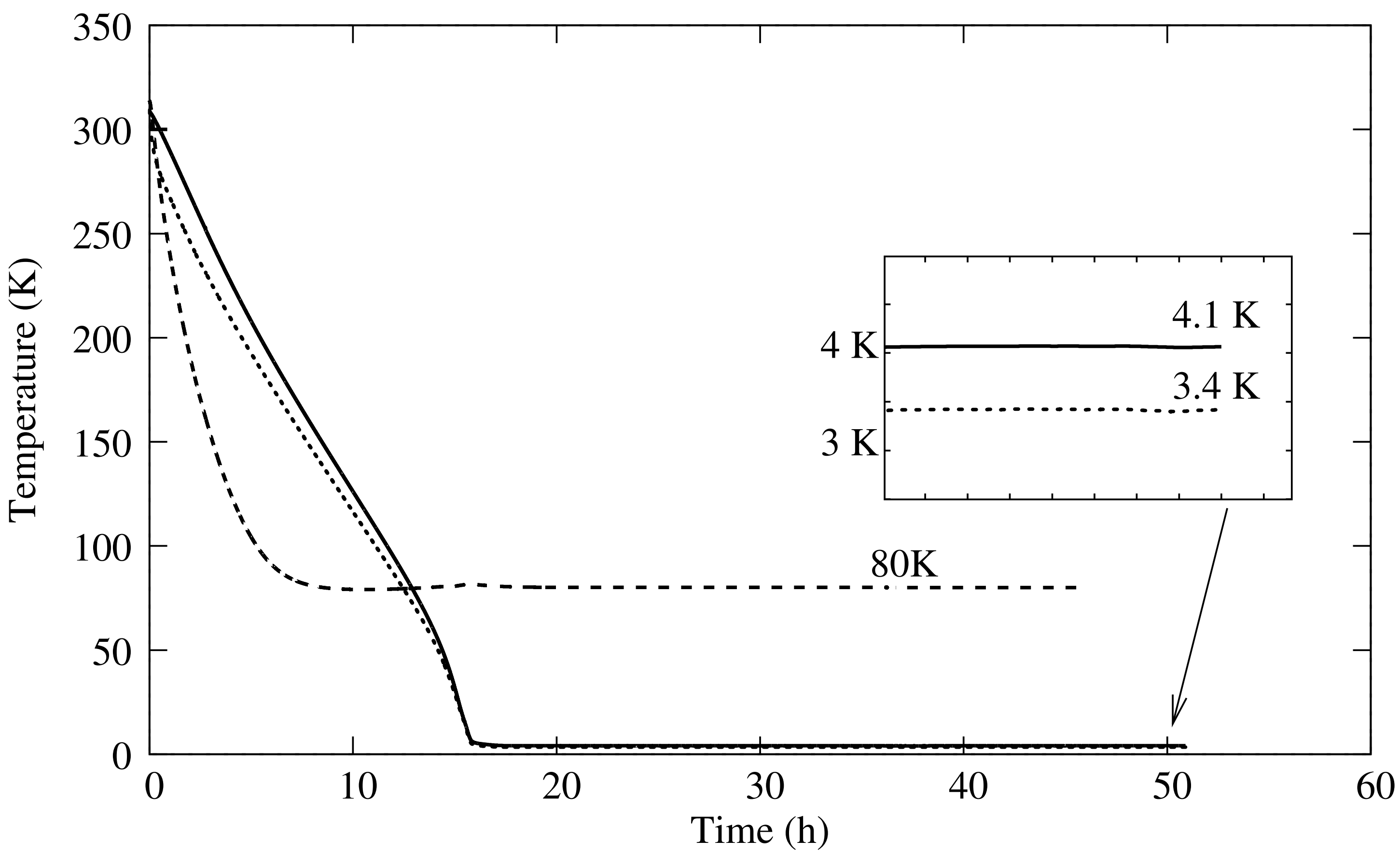
Suspension type	Axial damping (dB)	Transverse damping (dB)
Cylindrical rods	85	43
V-shaped	85	62

Modélisation mécanique des tresses très simplificatrice : ensemble de poutres en flexion

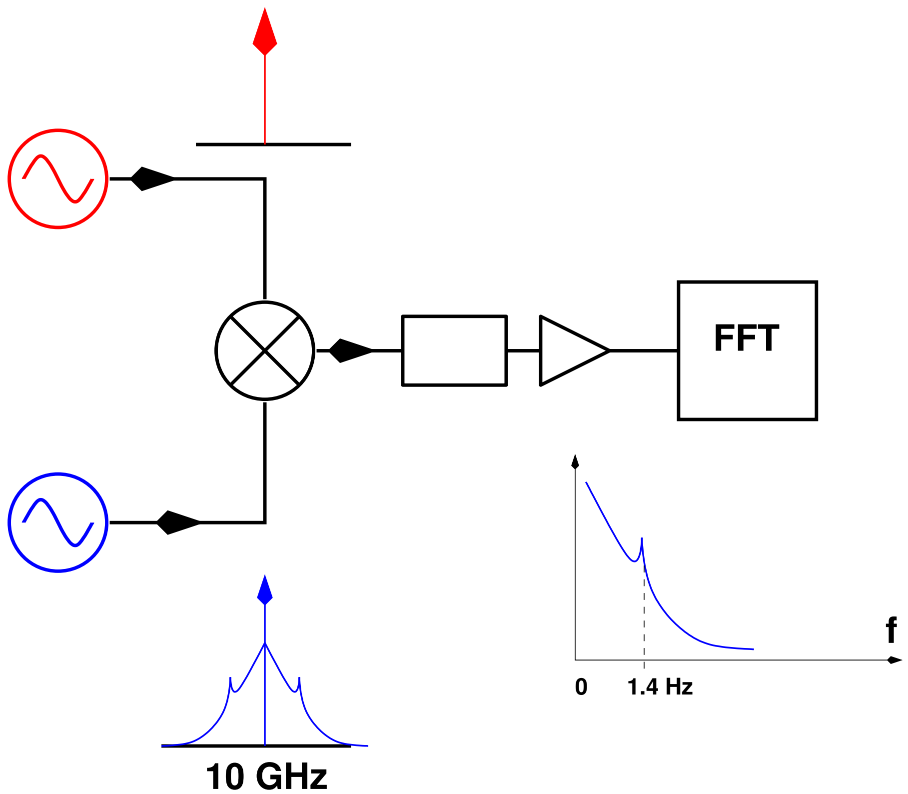
Réalisation : My Cryo Firm

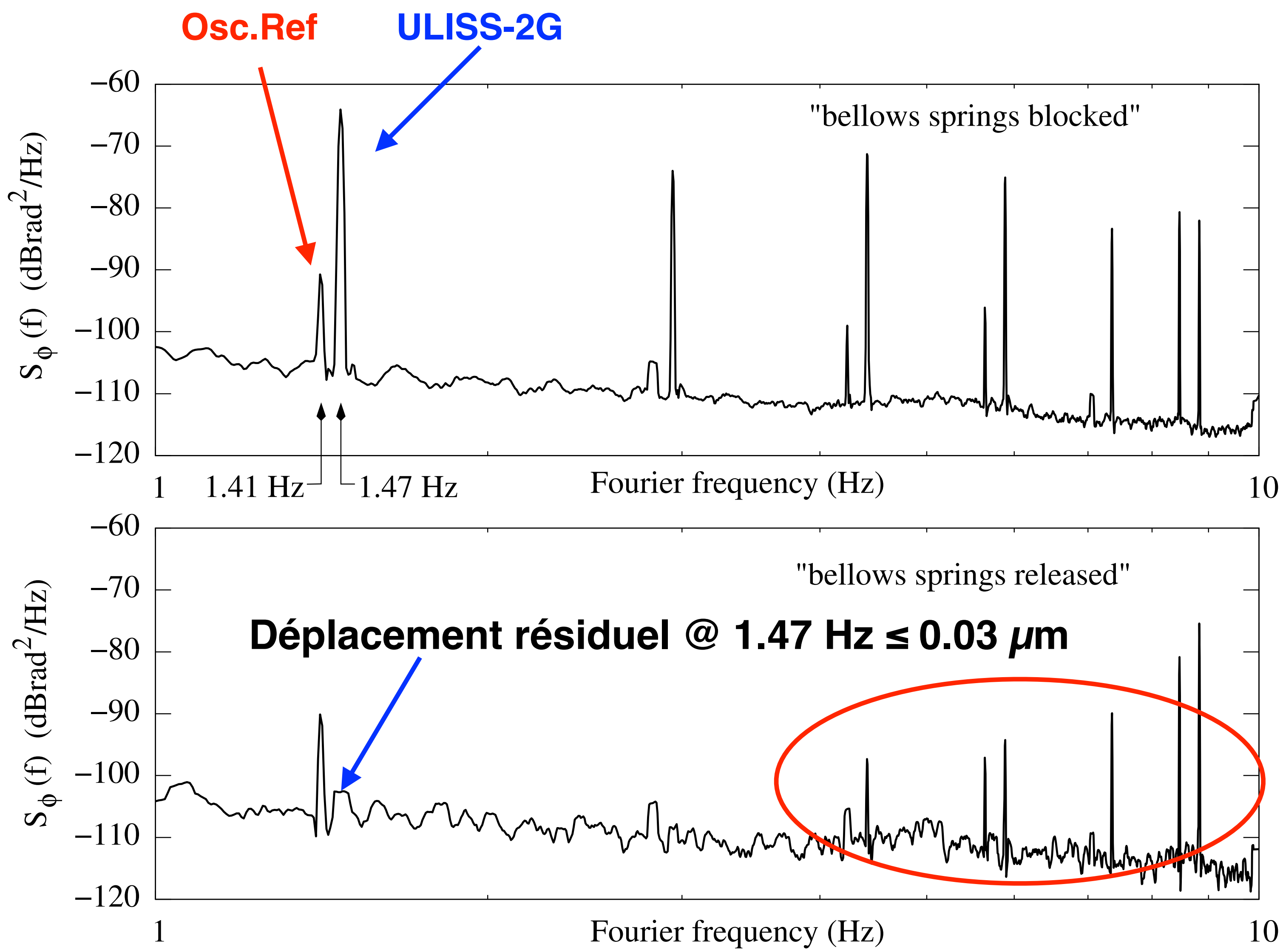


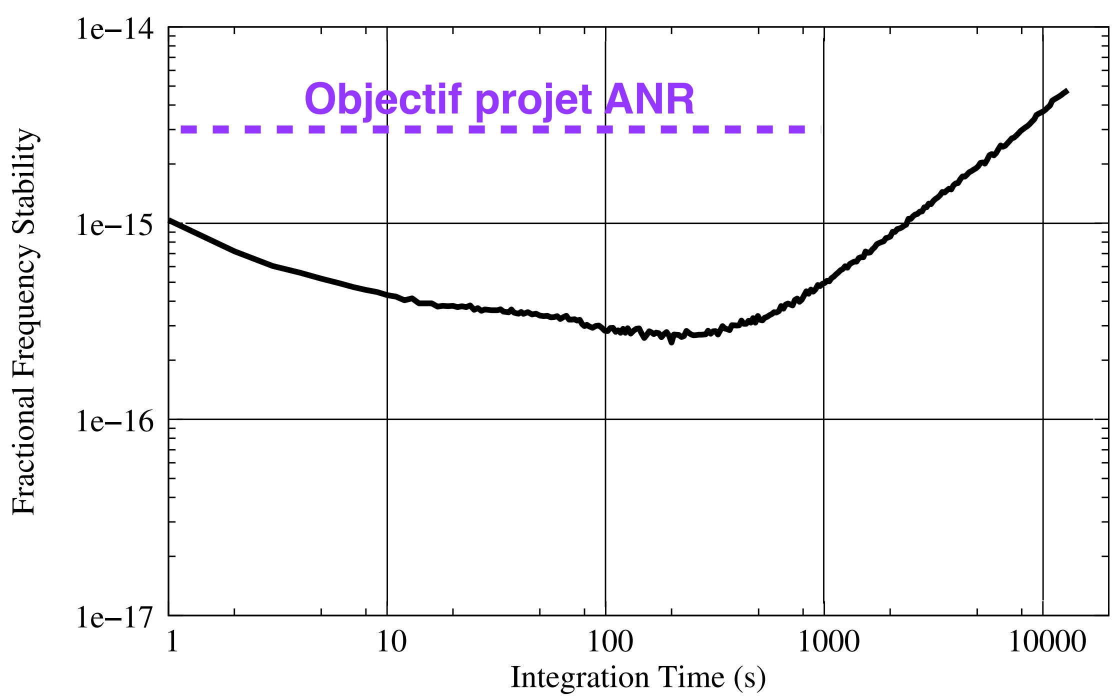




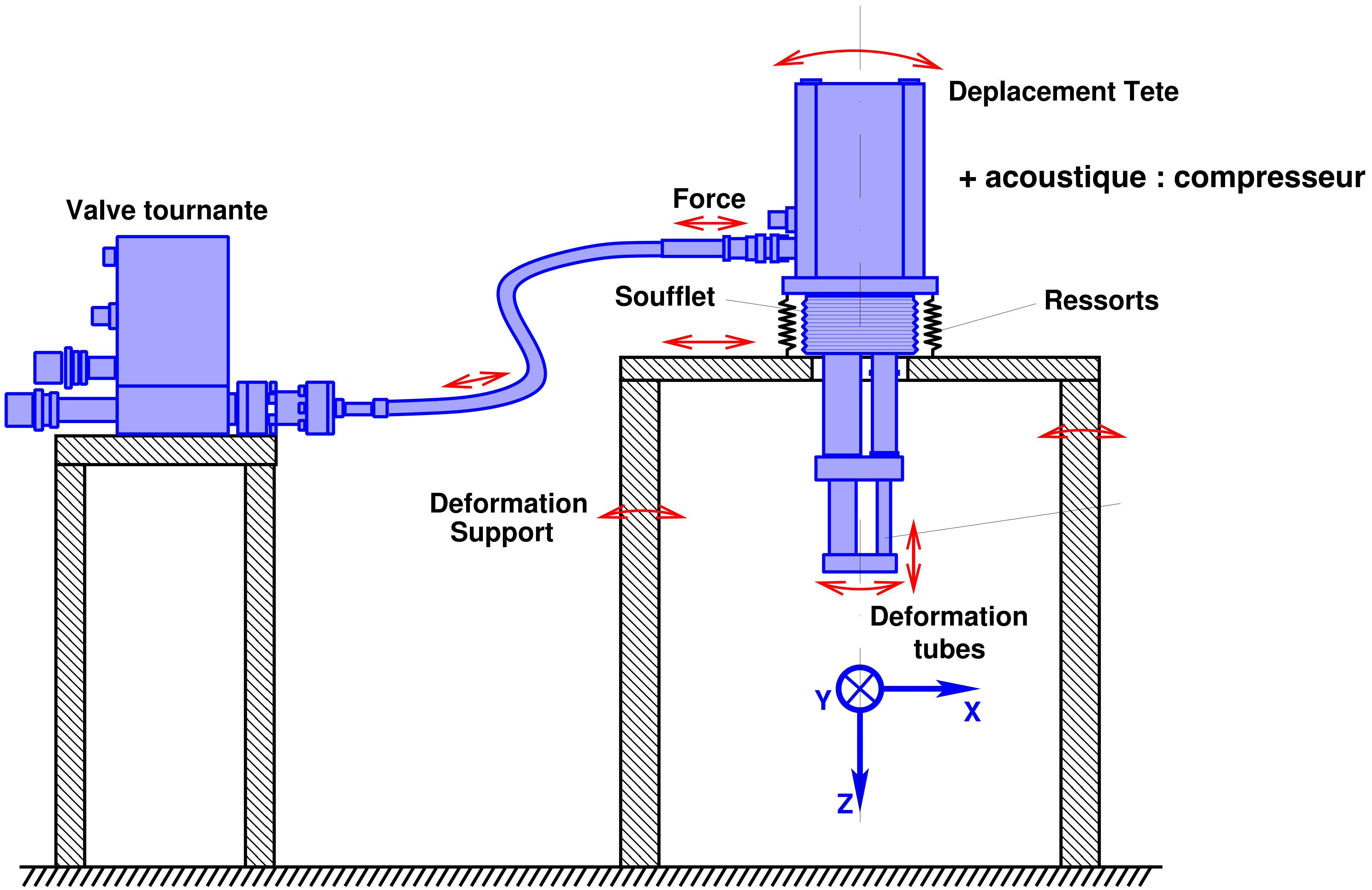
Vibrations, mesure du bruit de phase







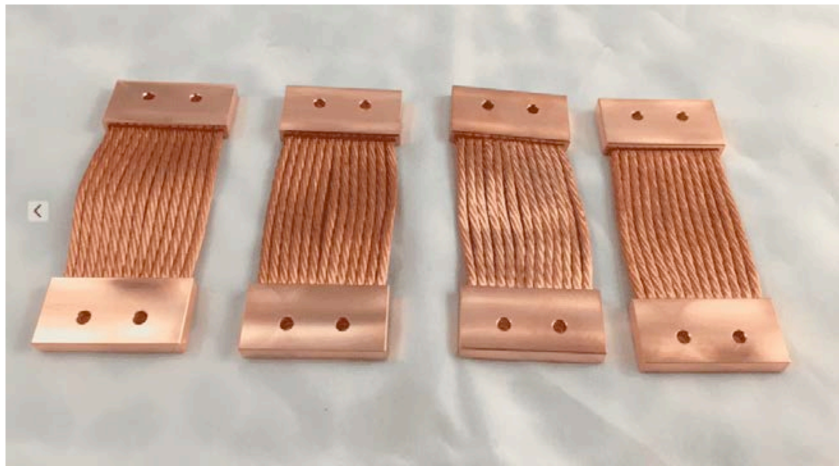
Vibrations



Typiquement :
Oz : 30 μm, Oy : 10 μm, Ox : 20 μm
@ 1.4 Hz

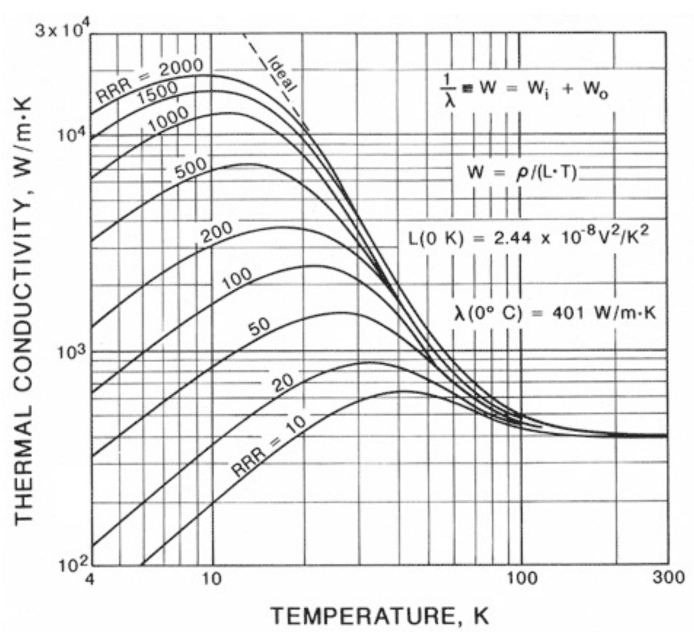
Liens flexibles : tresses de cuivre

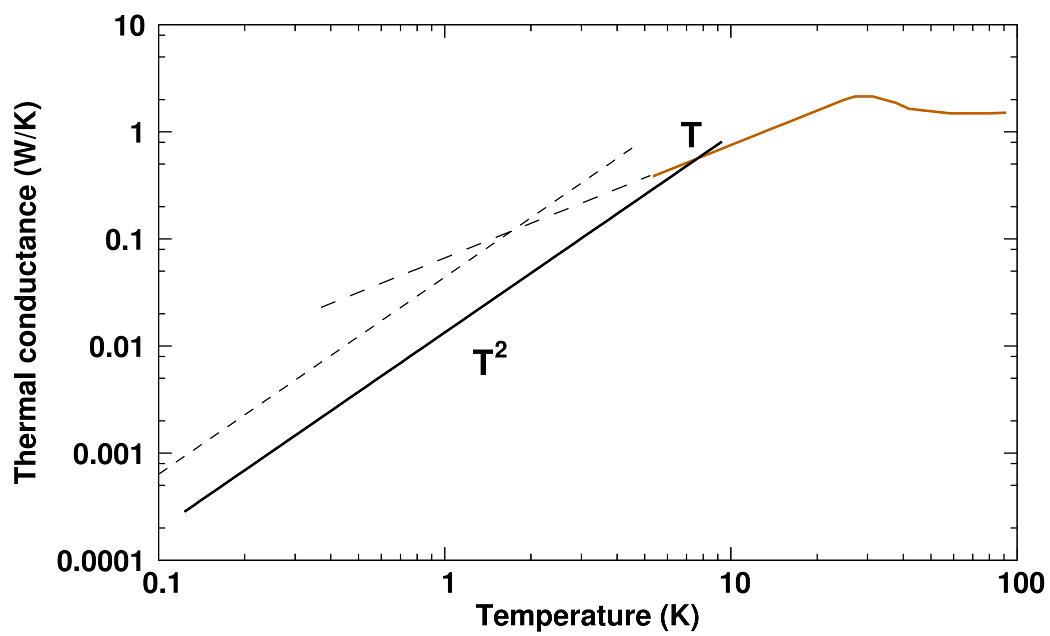
Fils + Embase Cu OFHC
Emboutissage à froid + Recuit

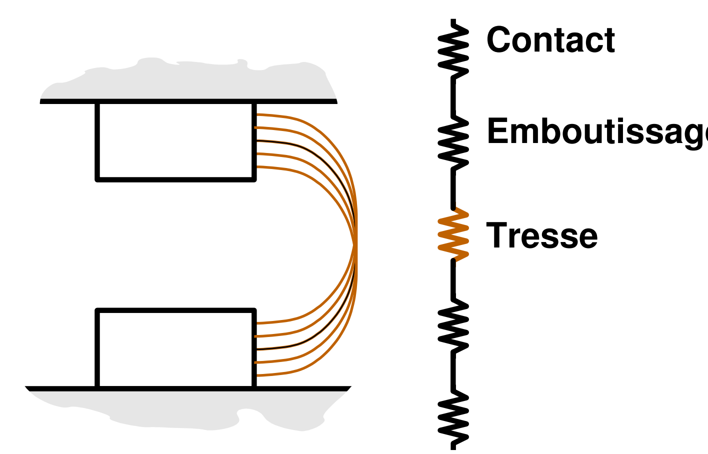


Technology Applications, Inc. (TAI)
Boulder, Colorado
pour équiper ULISS-2G : 6000 € (2013)

My Cryo Firm
Fontenay-sous-Bois
ULISS-2G : 1000 € (2022)







En pratique : R_{th} =1-2 k/W @ 70 K
R_{th} =5-7 k/W @ 6 K

Tresses Cu : k≠0.

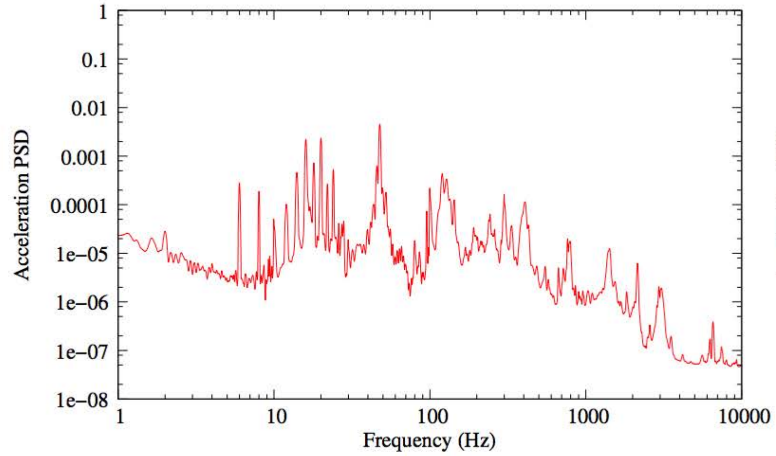


Figure 9: *Mylar rods and one braid connected.*

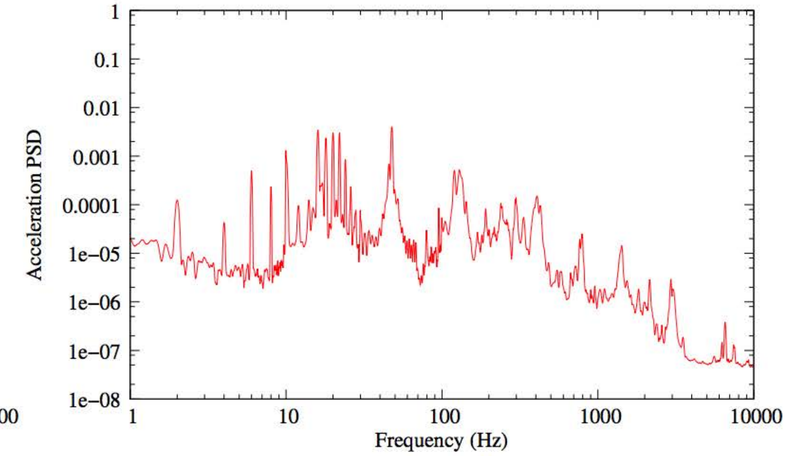


Figure 10: *Mylar rods and three braids connected.*

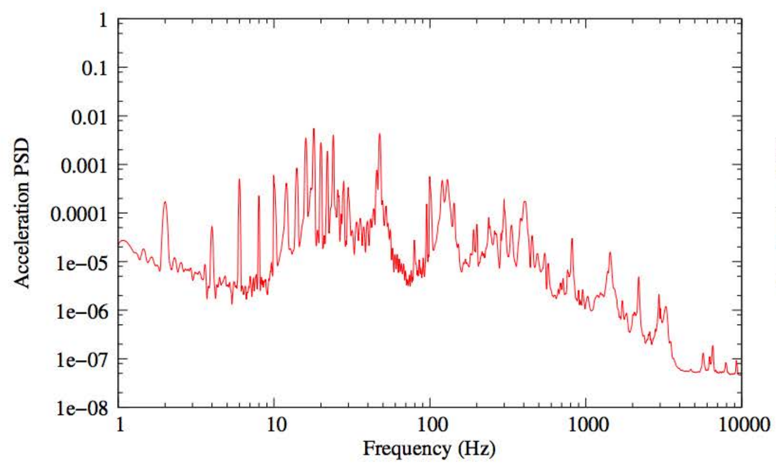


Figure 11: *Mylar rods and six braids connected.*

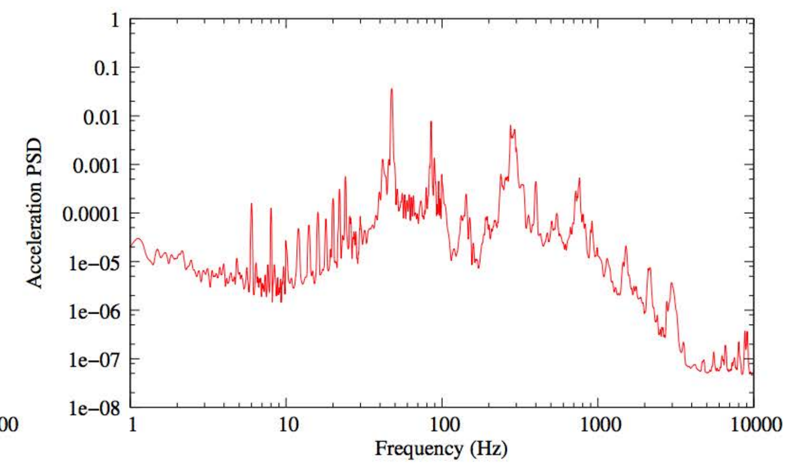
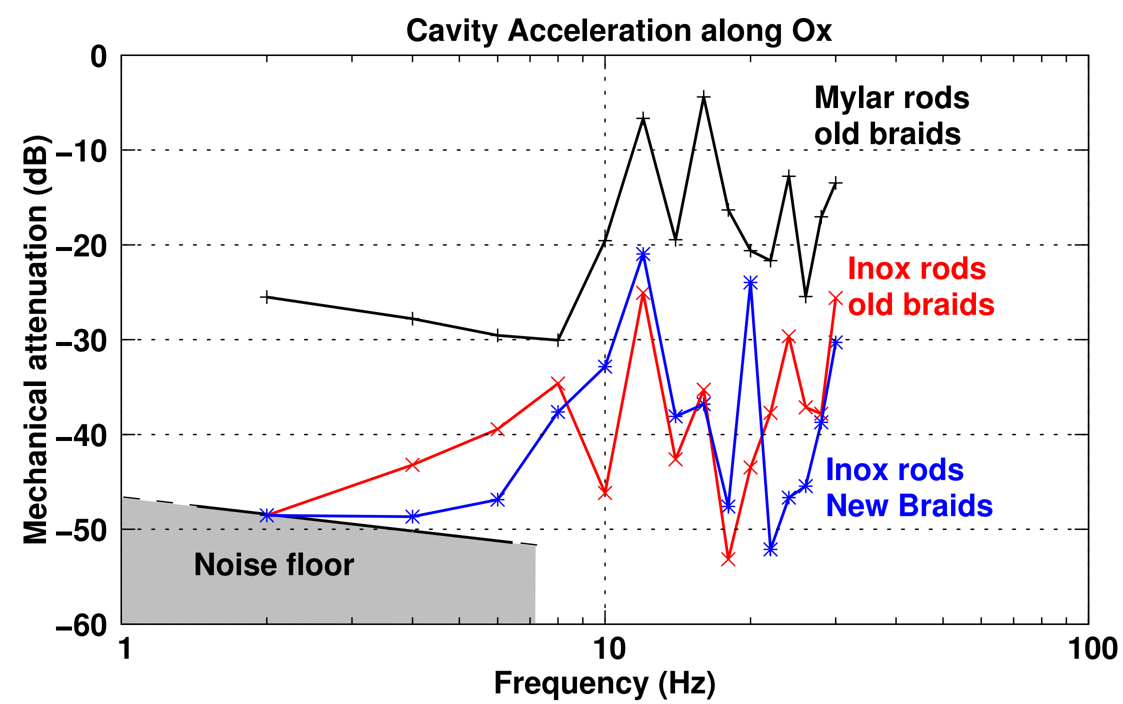


Figure 12: *Inox rods and six braids connected.*

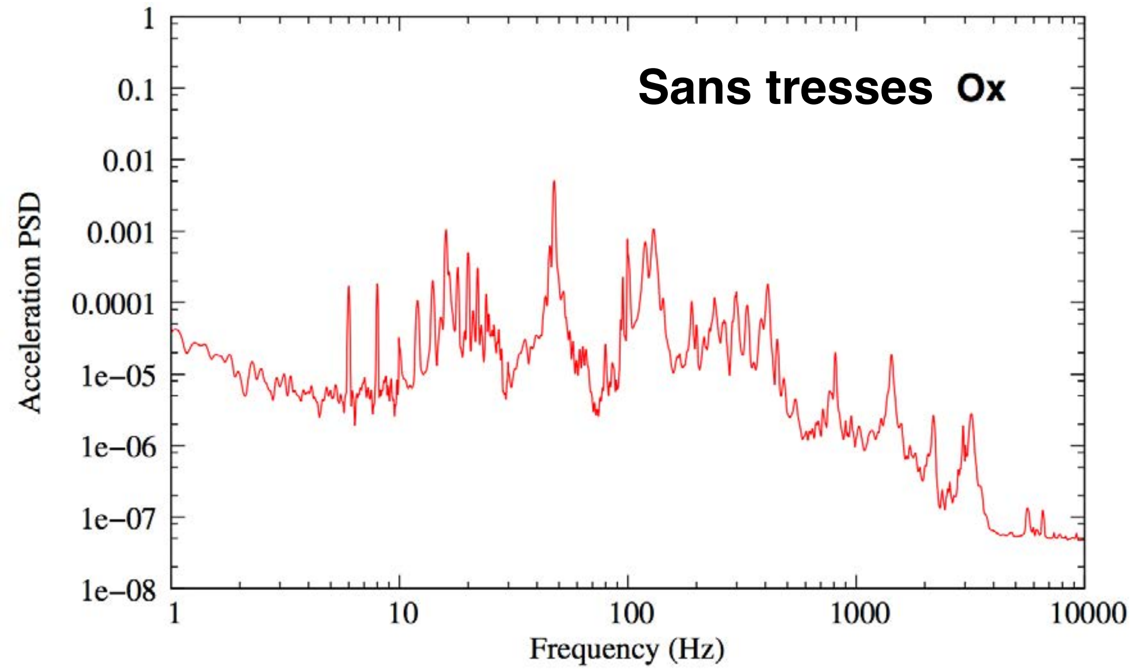
Table 3: Cavity: Acceleration and displacement along *Ox* at 2 Hz. RT above

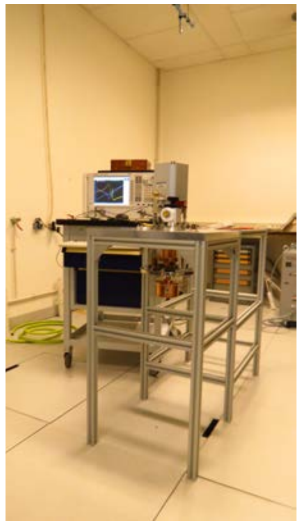
	Welded Steel profiles		
		RV above	
	γ (mm/s^2)	displacement (μm)	Attenuation (dB)
Mylar rods. no braids	$\leq 4.5 \times 10^{-3}$	≤ 0.03	≥ 44
Mylar rods. 1 braids	8.4×10^{-3}	0.05	39
Mylar rods. 3 braids	36×10^{-3}	0.2	26
Mylar rods. 6 braids	51×10^{-3}	0.3	23
Inox rods. 6 braids	$\leq 3 \times 10^{-3}$	≤ 0.02	≥ 48

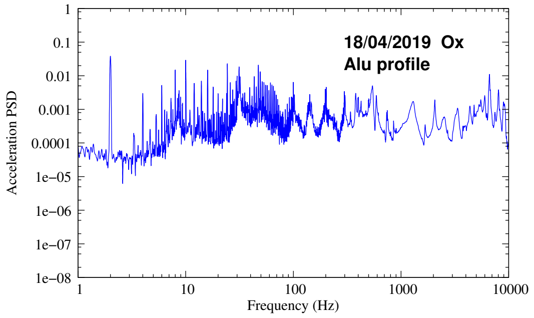


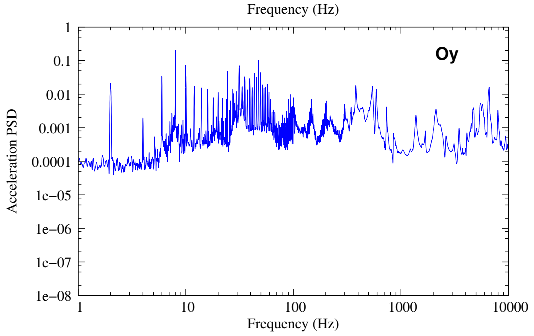
Recuit après écrouissage

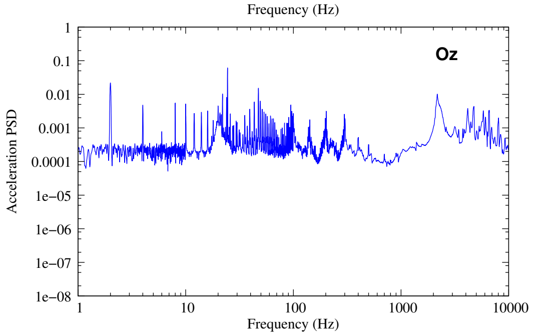
Contribution non négligeable de la structure : $k \neq \infty$

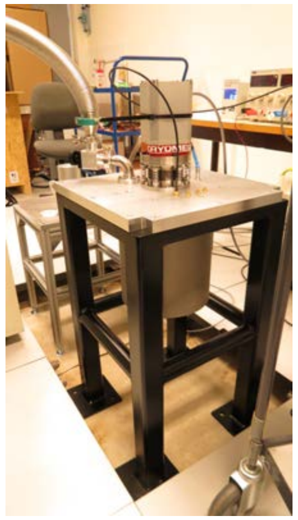


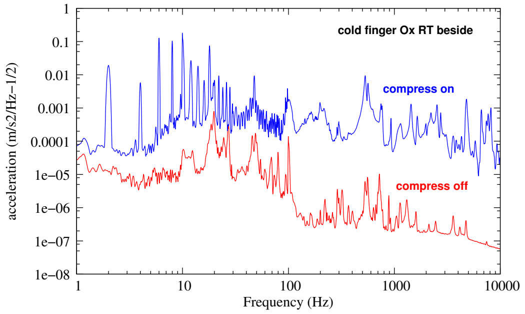


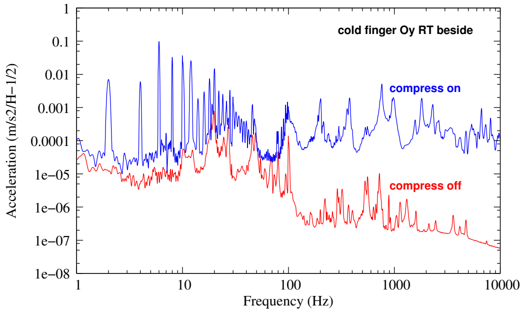


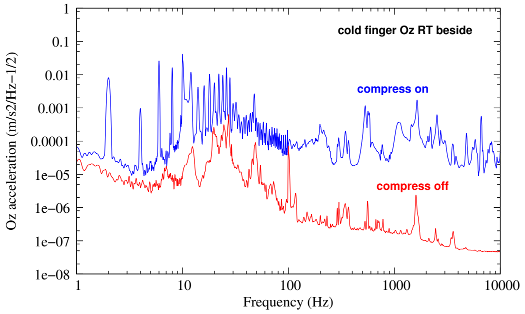


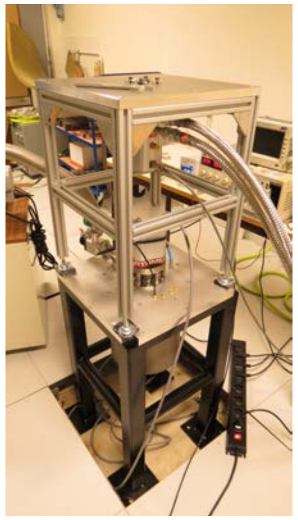


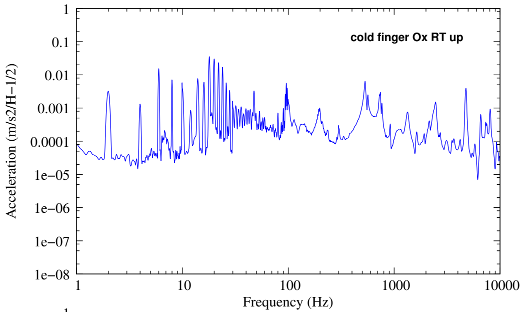


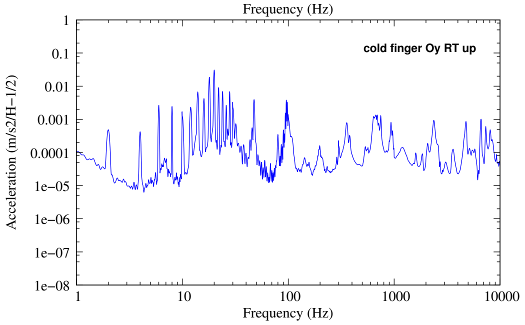


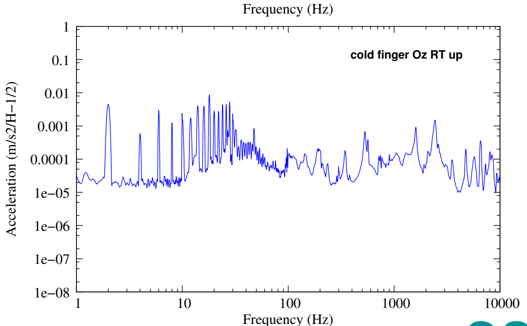


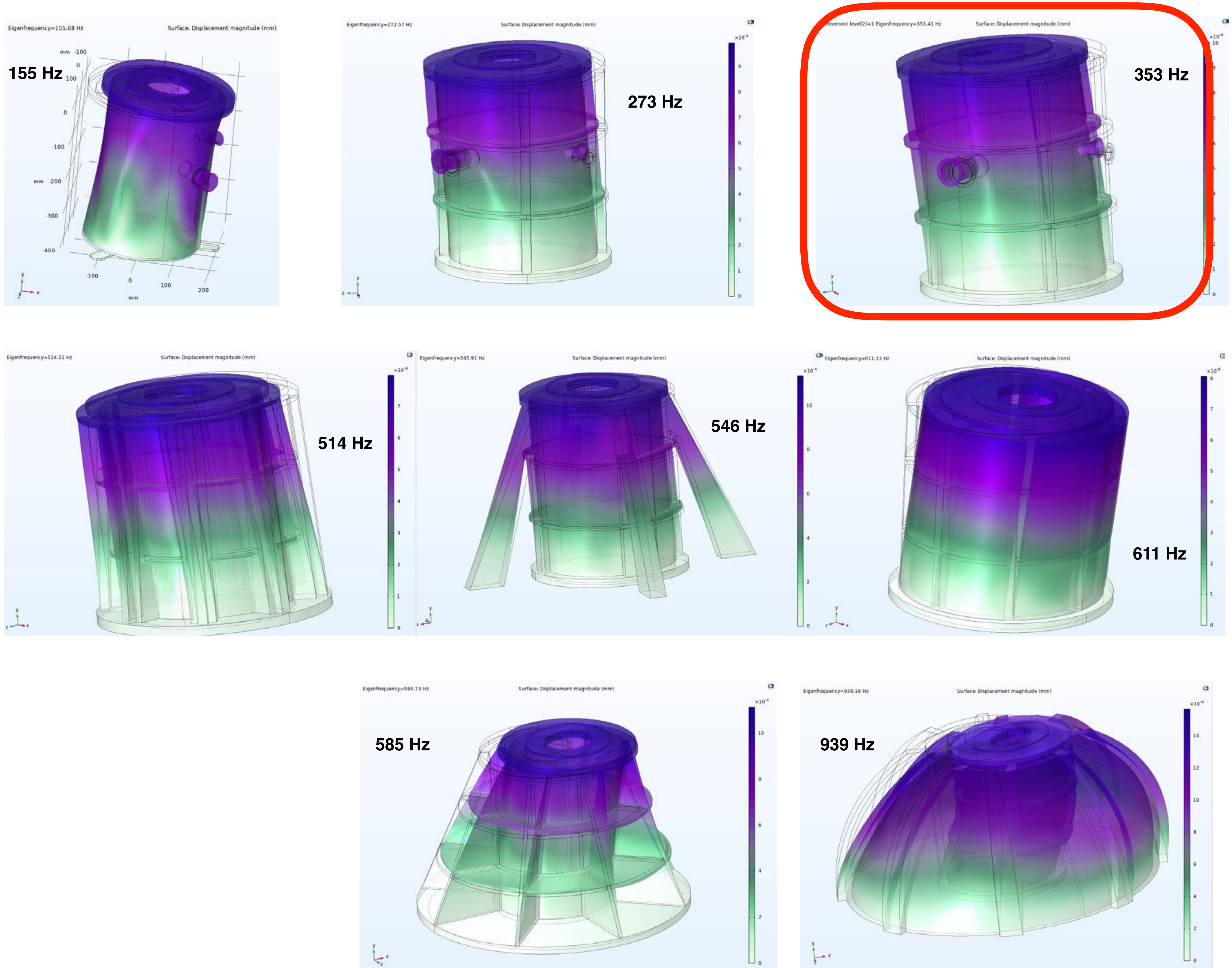








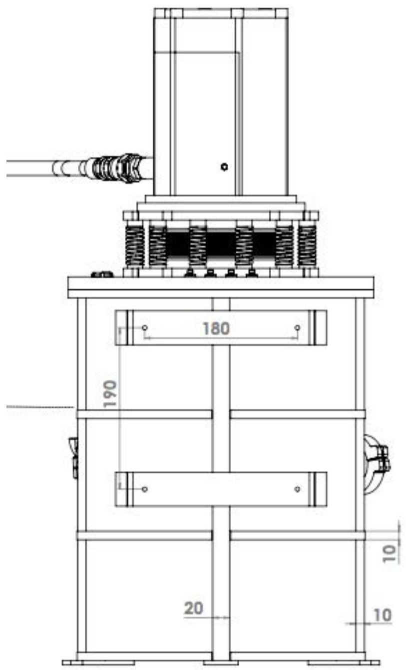


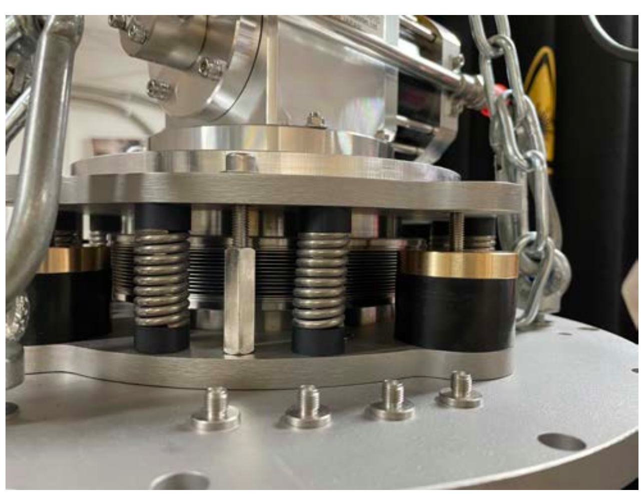

155 Hz
273 Hz
353 Hz
514 Hz
546 Hz
611 Hz
585 Hz
939 Hz

Nervures extérieures + Augmentation épaisseur

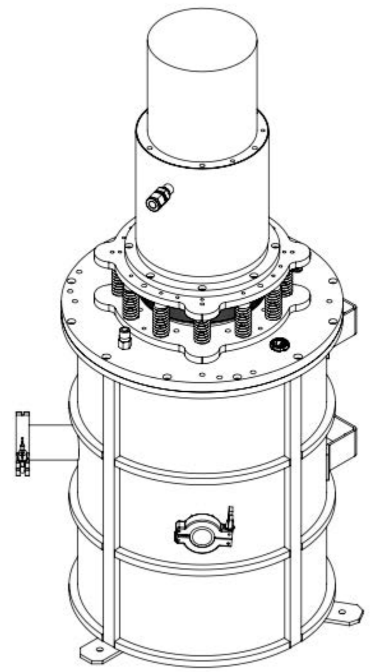
Un nouveau cryostat acceptant 3 types de cryogénérateurs :

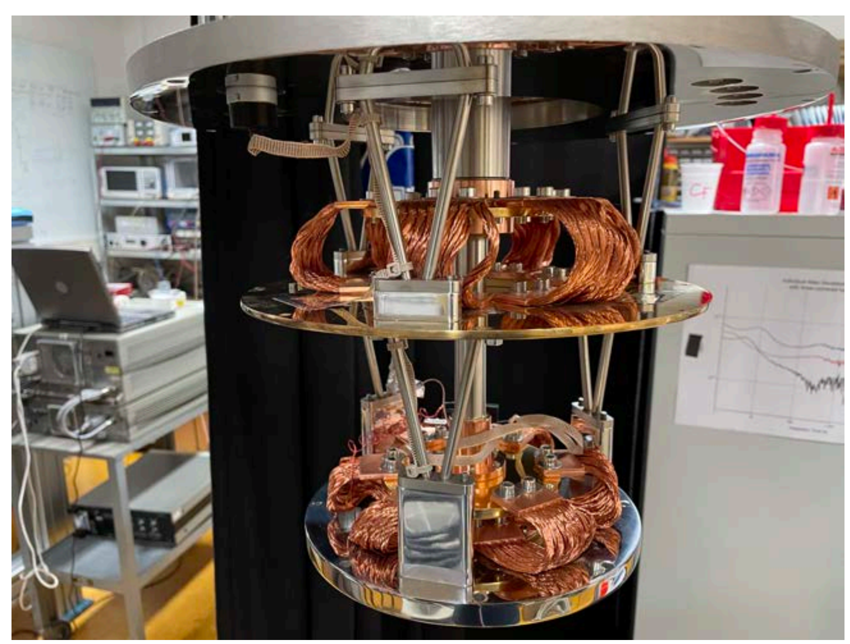
PT403 Cryomech





PTD4200 Transmit





RDK101 GM Sumitomo