



# Développement d'oscillateurs ultra-stables à FEMTO-ST



Yann Kersalé



# Départements de recherche de Femto-ST

## INFORMATIQUE DES SYSTEMES COMPLEXES



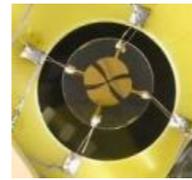
- Algorithmique numérique distribuée
- Systèmes répartis, ordonnancement
- Optimisation, mobility et networking
- Verification, validation de logiciels et systèmes embarqués

## AUTOMATIQUE & SYSTEMES MICRO-MECATRONIQUES (AS2M)



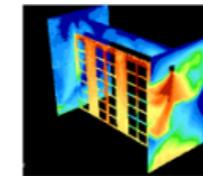
- Automatique
- Microrobotique
- Micromécatronique
- Micromanipulation and micro-assemblage
- Pronostics & Health Management (PHM)

## TEMPS-FREQUENCE



- Résonateurs et oscillators ultra-stables
- Acousto-électronique et piézoélectricité
- Métrologie et dispositifs radiofréquence

## ENERGIE



- Métrologie et modelisation énergétique
- Conception de systèmes énergétiques
- Echanges thermiques et écoulements fluidiques complexes

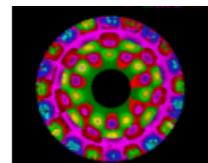
## OPTIQUE



- Photonique et telecommunications
- Nano-optique
- Optoélectronique
- Optique non

- Linéaire
- Photonique pour L'instrumentation biomédicale

## MECANIQUE (MEC'APPLI)

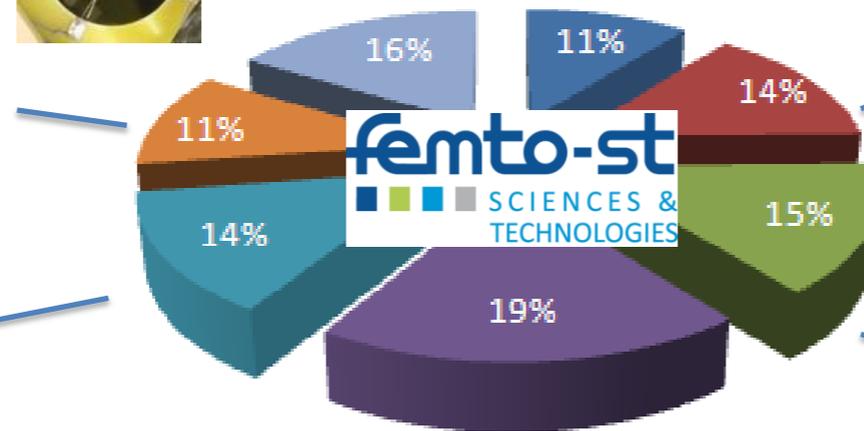


- Vibrations et acoustique
- Matériaux et structures
- Procédés de mise en forme et microfabrication
- Micro analyse des surfaces

## MICRO NANO SCIENCES & SYSTEMS (MN2S)



- Micro and nano-instrumentation
- Nanosciences
- Micro & nano-acoustique
- Microsystèmes multiphysiques
- Micro, nanomatériaux et surfaces

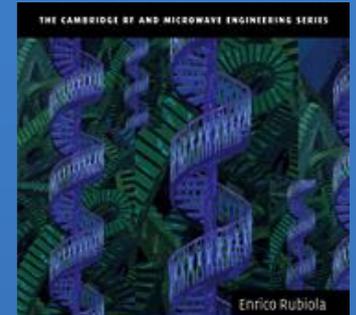
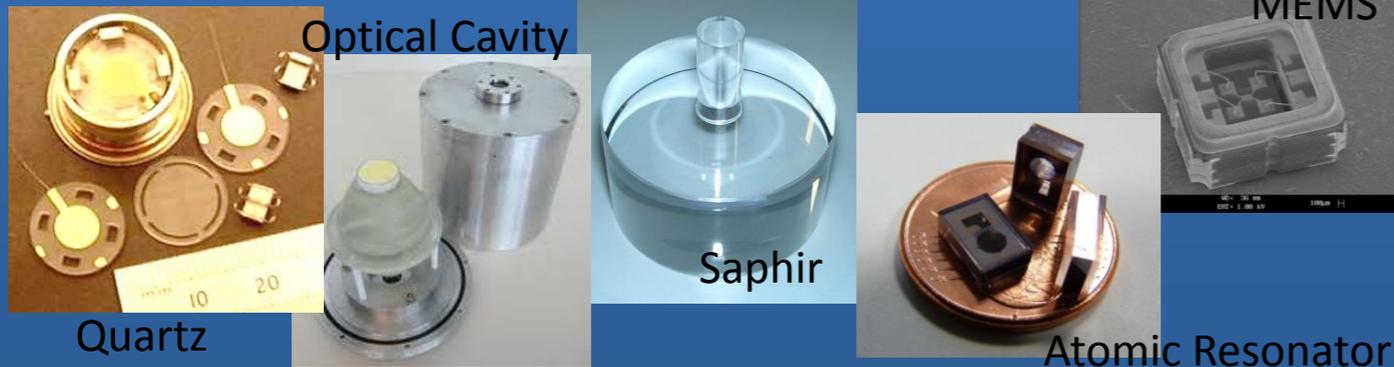


# Département Temps-Fréquence.

Héritier de la tradition horlogère et métrologique Francomtoise

**Références de fréquences:** Nous concevons des résonateurs nécessaires aux applications les plus exigeantes: spatial, radio astronomie, télécommunications, radar, métrologie et physique fondamentale...

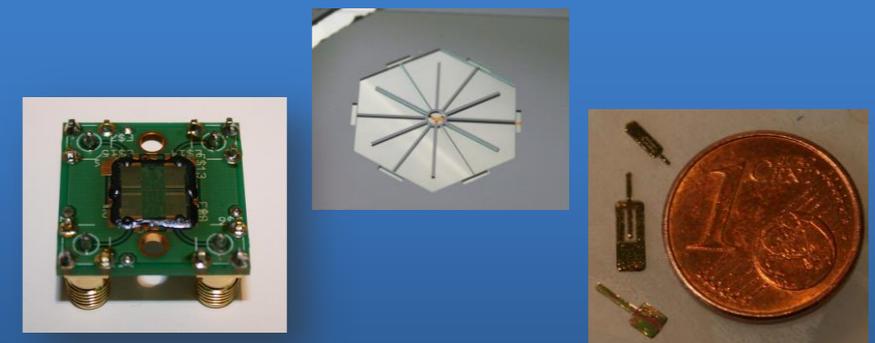
Ces références sont basés des *résonateurs* (équivalent du pendule de l'horloge comtoise) qui fixe la fréquence. Différents types de résonateurs sont étudiés en fonction de la fréquence (RF, VHF, micro-onde, optique) et de l'application.



Phase Noise and Frequency Stability in Oscillators

**Métrologie :** Le bruit de phase et la stabilité de fréquence sont les caractéristiques les plus importantes d'un oscillateur. Nous étudions et mettons au point des bancs de mesure permettant la caractérisation de sources de signaux à l'état-de-l'art. Notre activité de recherche est complétée par une activité de service agréée IS9001 pour la caractérisation de la stabilité de fréquence.

**Capteurs :** Pour réaliser un oscillateur performant, le résonateur doit être insensible aux perturbations extérieures. Il est cependant possible de magnifier sa sensibilité à un paramètre physique: on réalise alors un capteur. Nos capteurs à sortie de fréquence délivre un signal qui peut être traité directement par des circuits numériques. Ils procurent une excellente résolution et peuvent être interrogés à distance.

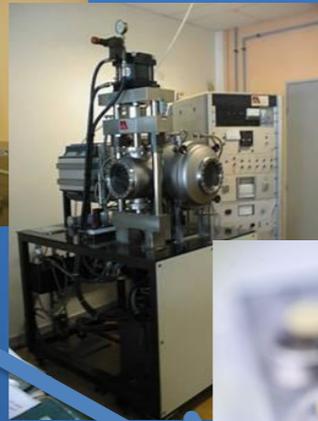


# Département Temps-Fréquence.

Des matériaux aux systèmes

## Caracterisation et mise en forme Matériaux piézoélectriques et matériaux durs

X-ray & IR    Packaging



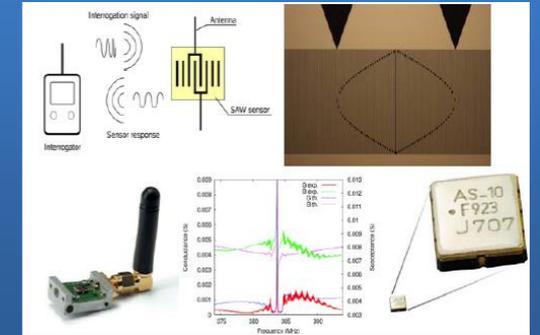
Sciage  
Polissage  
Rodage



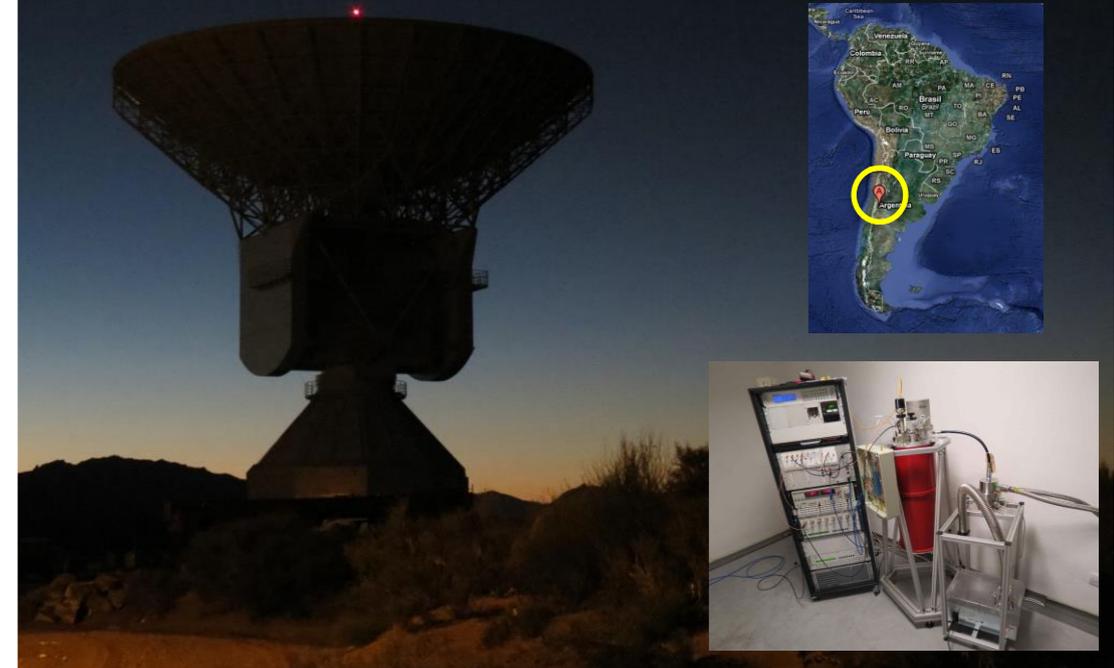
Usinage Ultra-sonore



## Electroniques ultra-faible bruit analogiques et numériques



## Oscillateur cryogénique pour la navigation spatiale



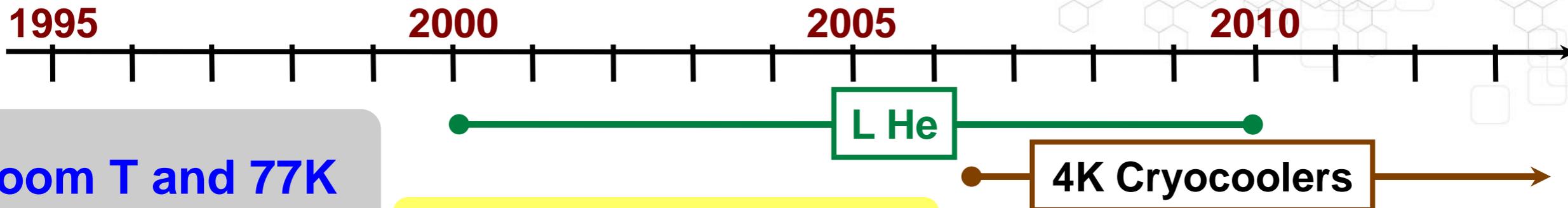
## LNE-LTFB Service de calibrage certifié COFRAC

Le LNE-LTFB est le laboratoire de référence national pour la mesure de la stabilité de fréquence.

Il est répertorié au plus niveau international dans CMCs publiés par le BIPM.



# Cryogenic sapphire oscillator at FEMTO-ST



## Room T and 77K



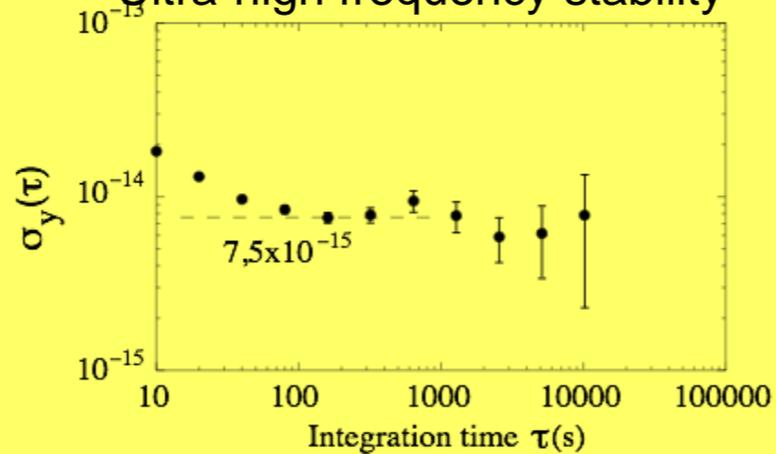
Low phase noise Osc.  
5 GHz, 10 GHz, 26 GHz

Thermal stabilisation

Thermal compensation  
(dielectric thin films  
deposition)



## Ultra-high frequency stability



## ELISA project

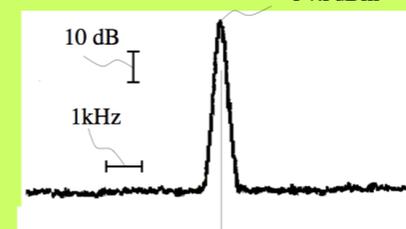
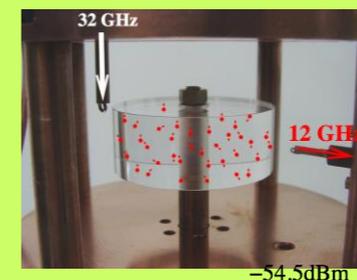


## ULISS Project

A new CSO in a small van to visit Europe



## Fe<sup>3+</sup> maser effect in WG mode sapphire resonator

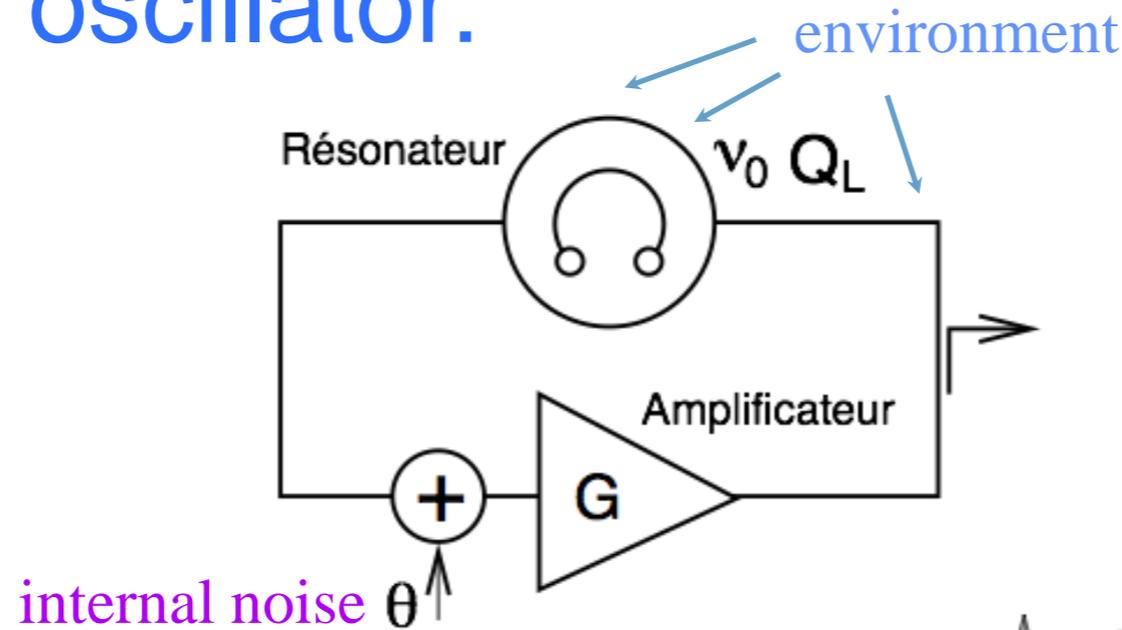


12.038,135 GHz



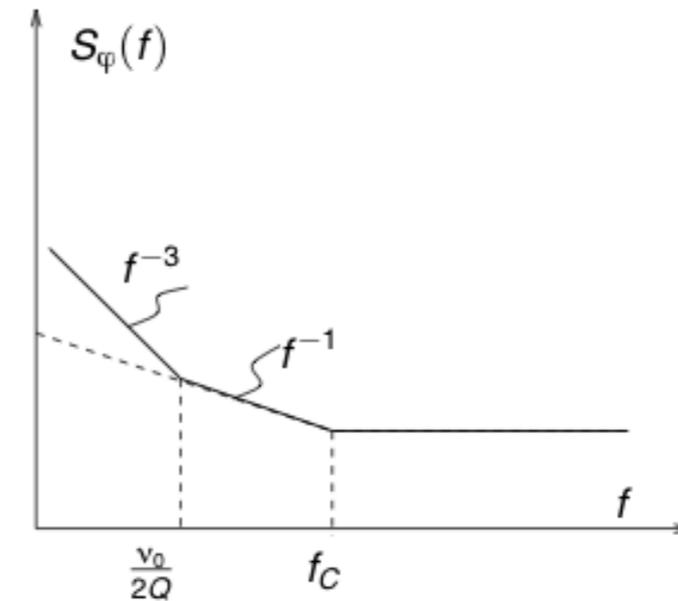


# To build a good oscillator:

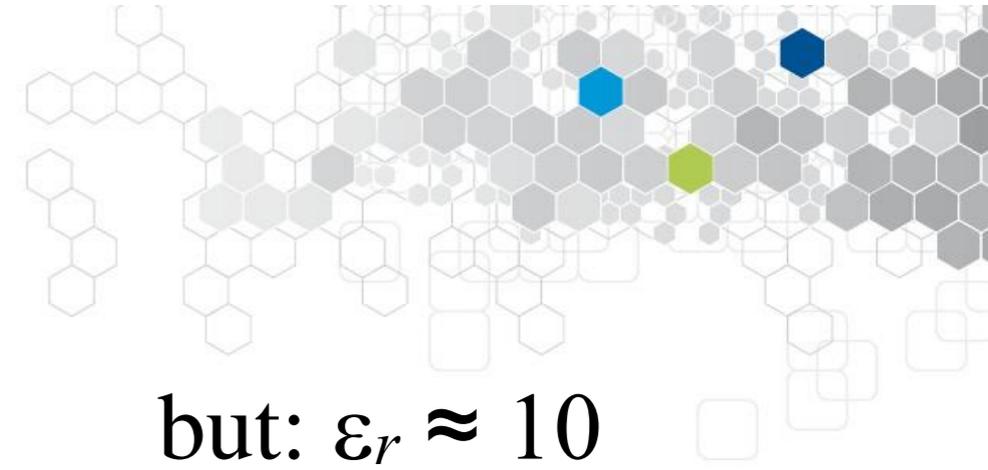


- High Q-factor

$$S_{\varphi}(f) = \left( 1 + \frac{v_0^2}{4Q_L^2} \frac{1}{f^2} \right) S_{\Delta\theta}(f)$$

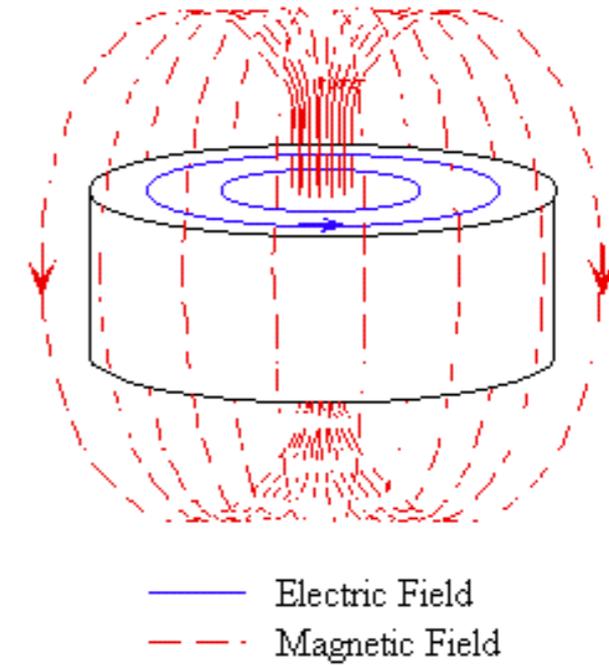
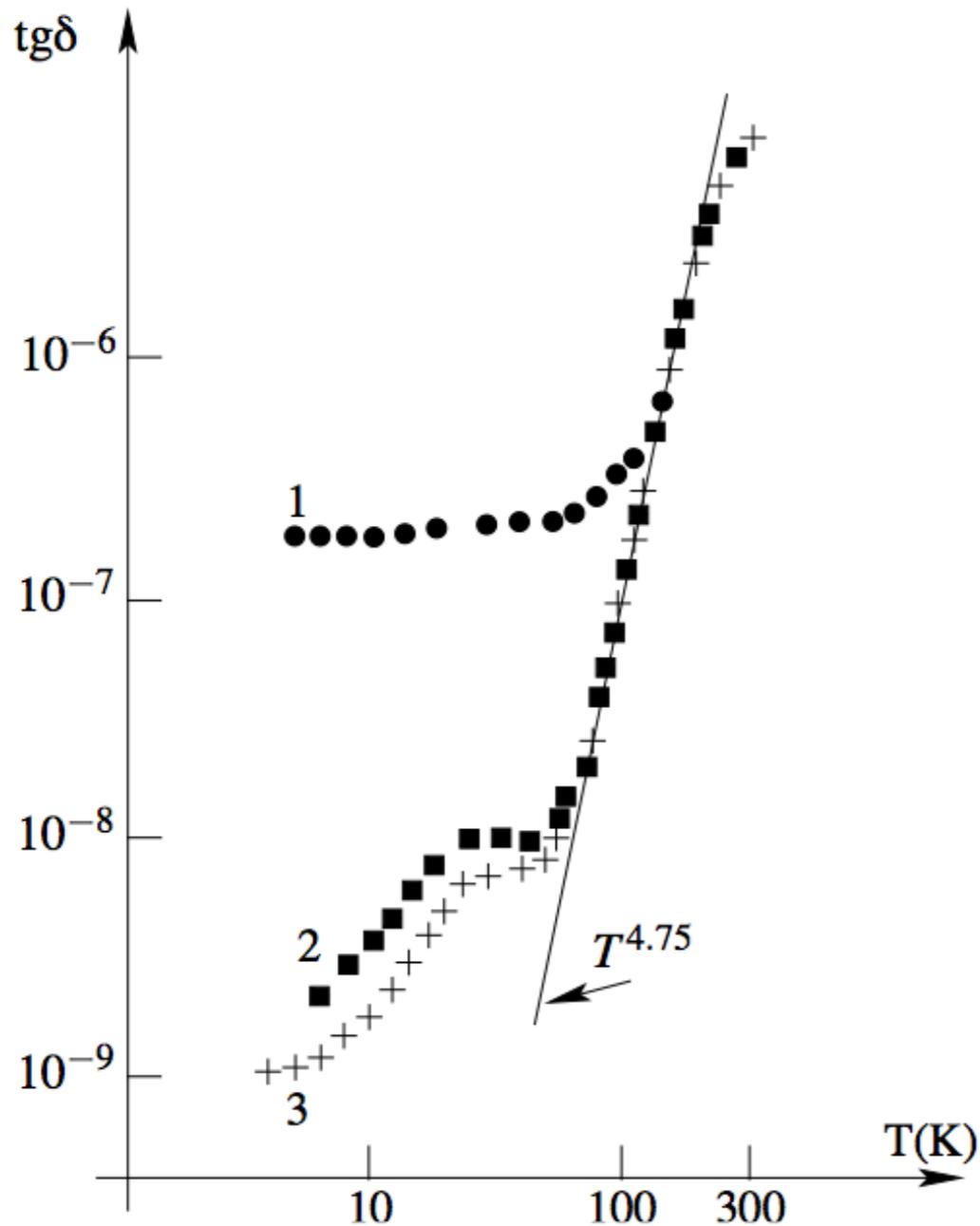


- Low sensitivity to environment  
 (especially temperature fluctuations)



but:  $\epsilon_r \approx 10$

Al<sub>2</sub>O<sub>3</sub> monocrystal: the lowest dielectric losses in X-band



$$\frac{1}{\nu} \frac{\partial \nu}{\partial T} \approx -\frac{1}{2} \frac{1}{\epsilon_{\parallel}} \frac{\partial \epsilon_{\parallel}}{\partial T} \approx \left\{ \begin{array}{l} -70 \text{ ppm/K @ 300K} \\ -10 \text{ ppm/K @ 77K} \end{array} \right\}$$

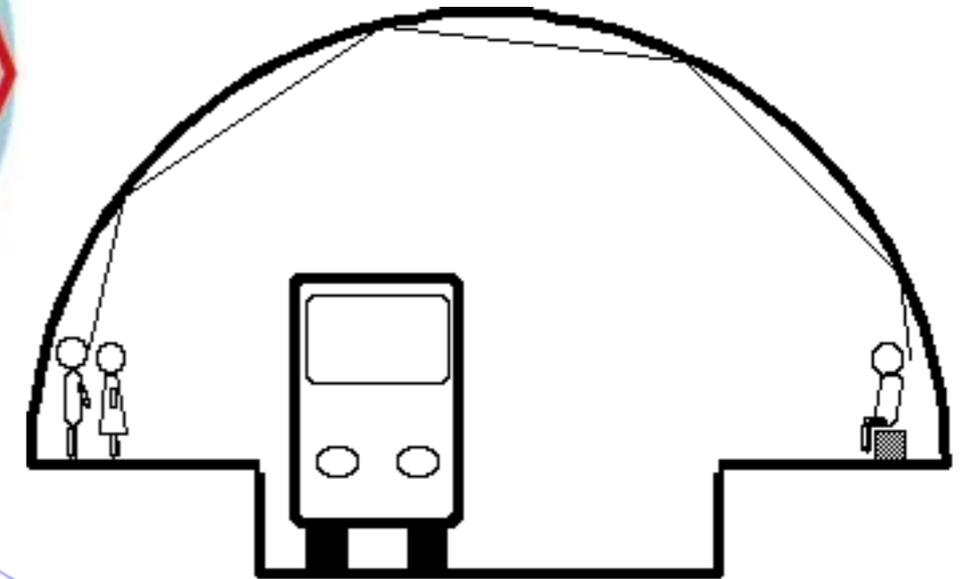
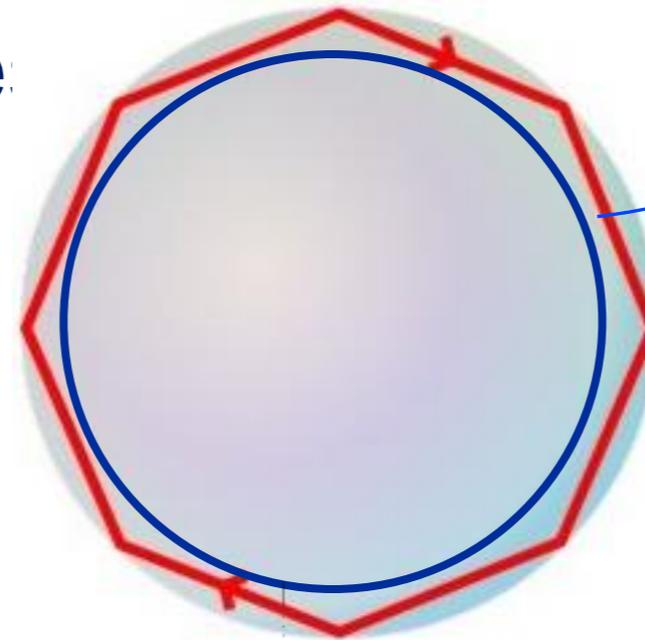
$$\frac{1}{\nu} \frac{\partial \nu}{\partial T} \approx -\frac{1}{2} \frac{1}{\epsilon_{\perp}} \frac{\partial \epsilon_{\perp}}{\partial T} \approx \left\{ \begin{array}{l} -50 \text{ ppm/K @ 300K} \\ -6.5 \text{ ppm/K @ 77K} \end{array} \right\}$$



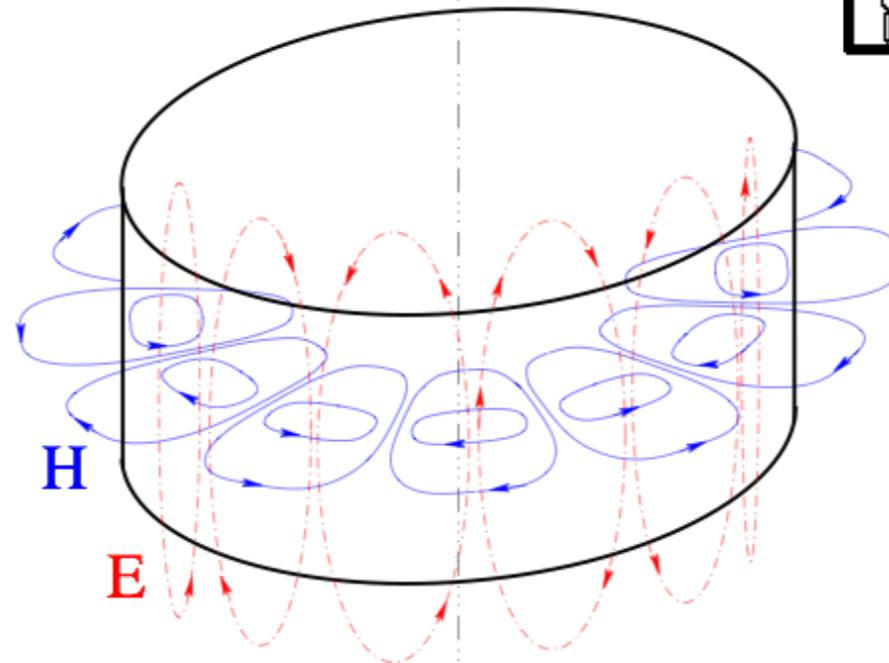
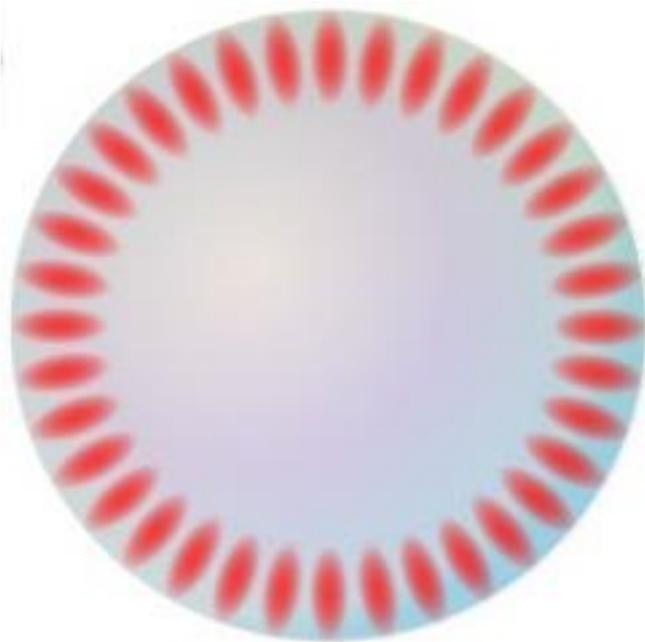
# Whispering Gallery Mode

Total reflexion

Confinement inside the dielectric



Electromag. fields



WGH mode

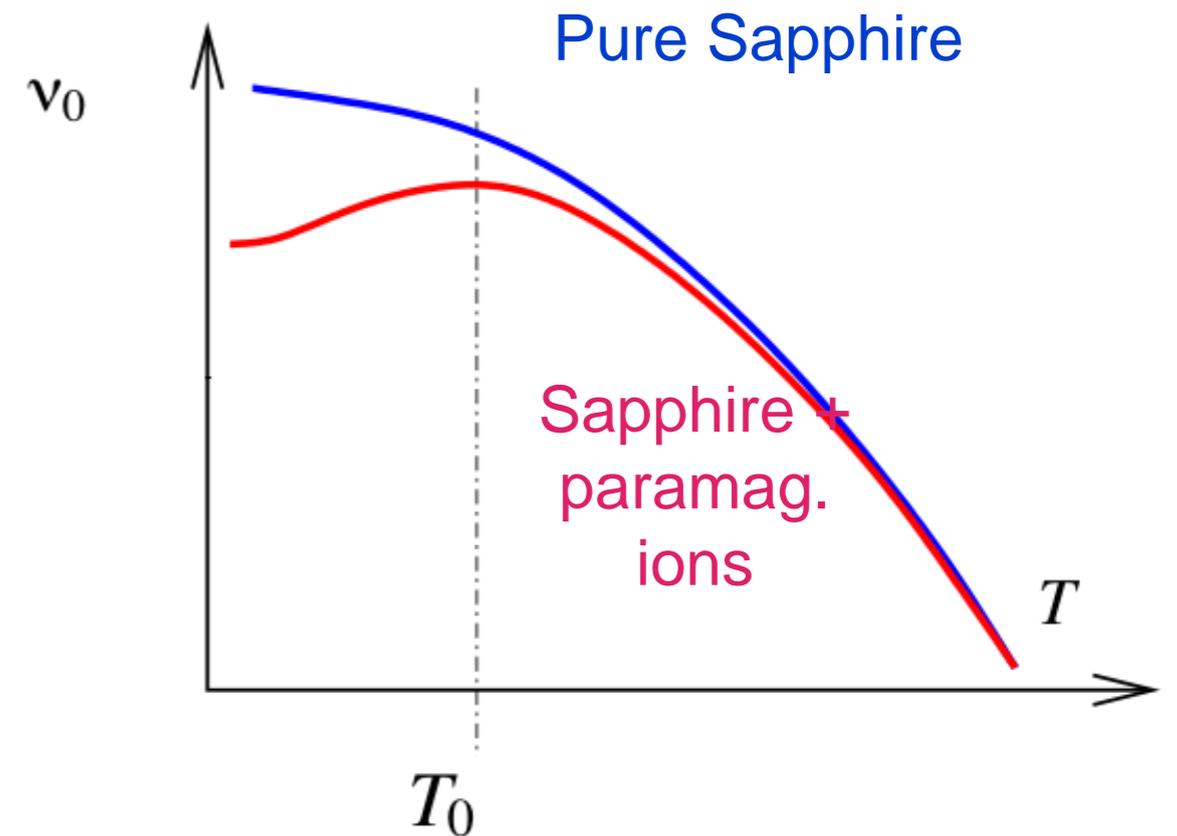
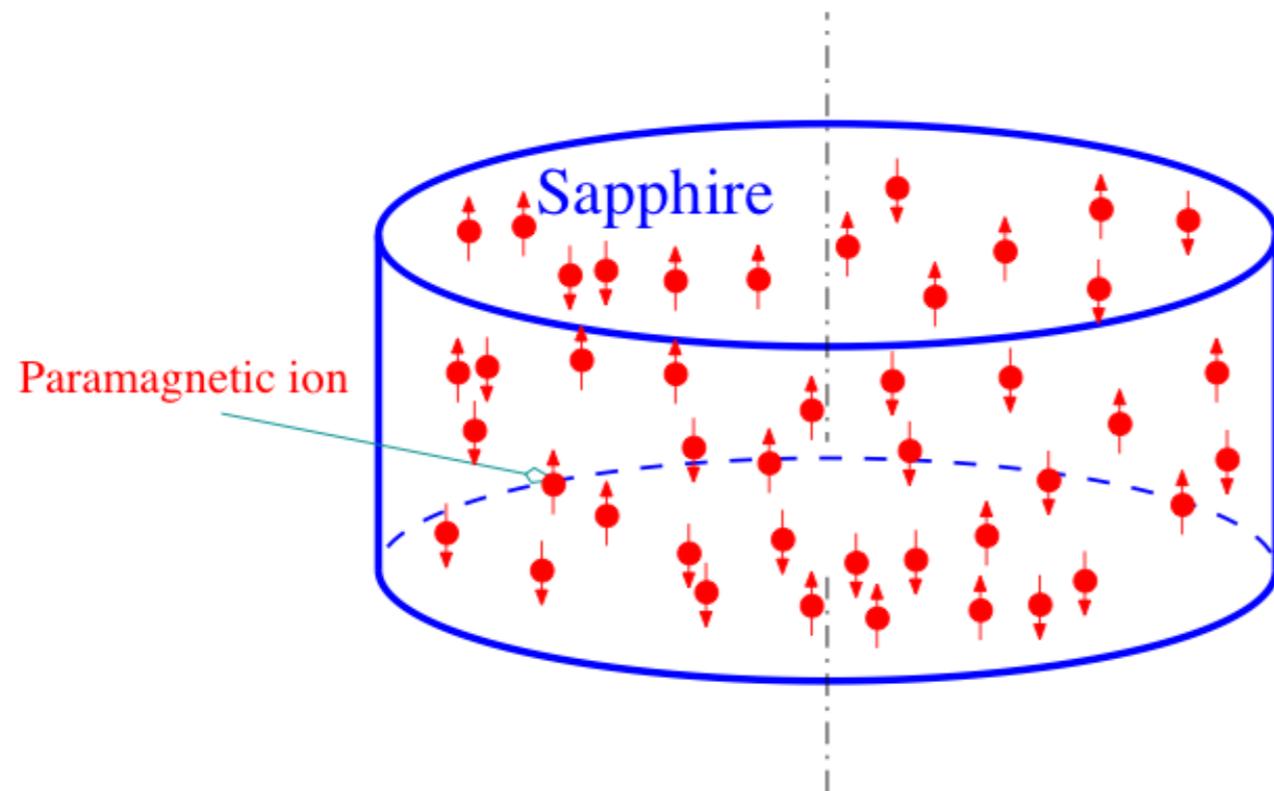
$$Q_0 \sim \frac{1}{\text{tg}\delta} \rightarrow \sim 10^9 @ 4\text{K}$$



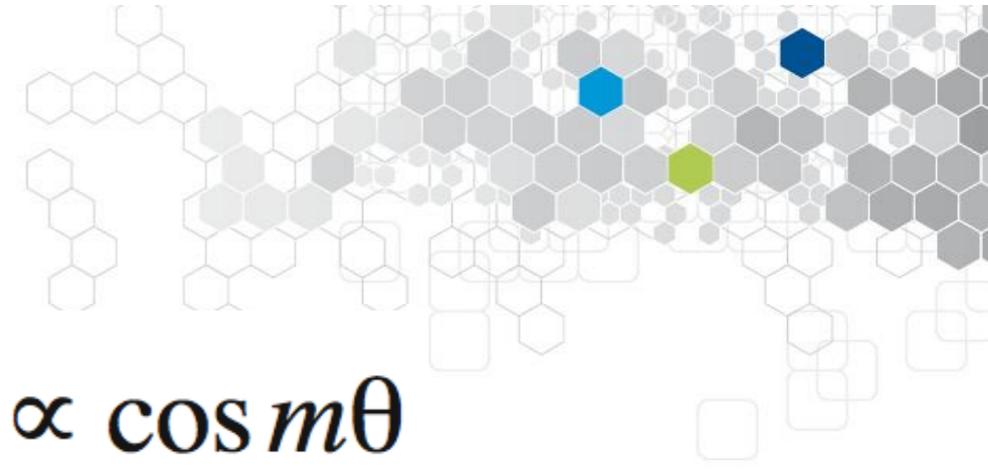


## Thermal compensation

paramagnetic impurities:  $\text{Fe}^{3+}$   $\text{Cr}^{3+}$ ,  $\text{Mo}^{3+}$ ,  $\text{Ti}^{3+}$



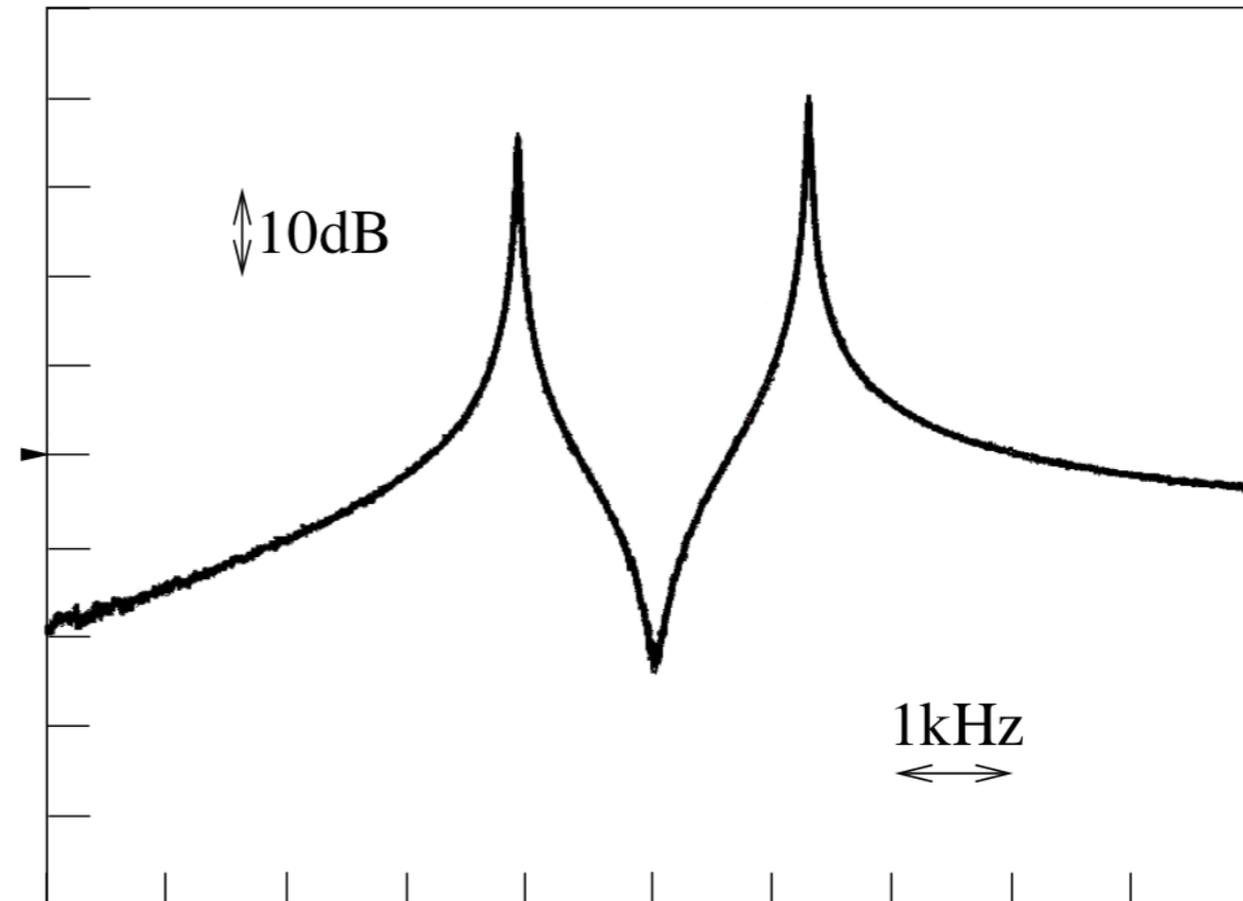
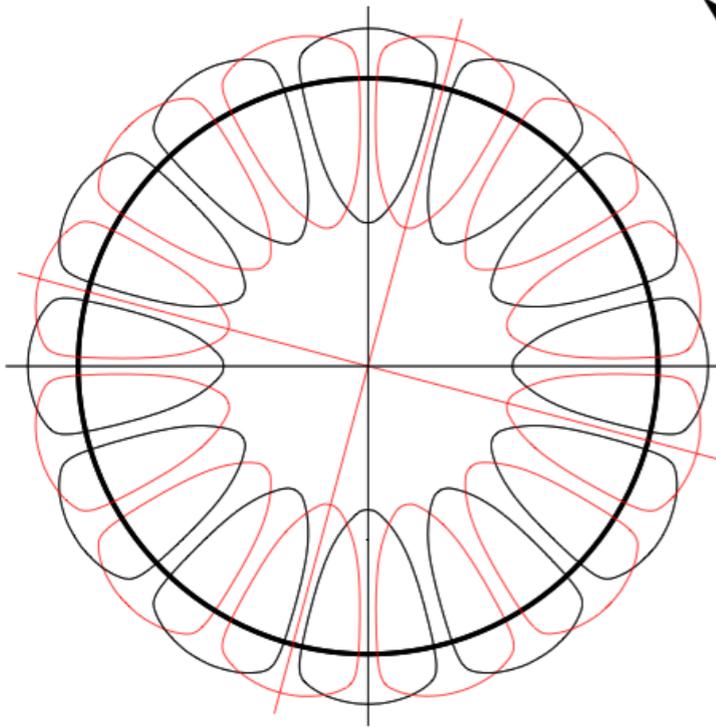
$$T_0 \sim 6 \text{ K}$$



# Mode degeneracy

$$H_{\theta}^{(+)} \propto \cos m\theta$$

$$H_{\theta}^{(-)} \propto \sin m\theta$$





Power sensitivity  $\frac{1}{\Delta P} \frac{\Delta \nu}{\nu} \sim 4 \times 10^{-11} / \text{mW}$

Power regulation mandatory

Vibration sensitivity

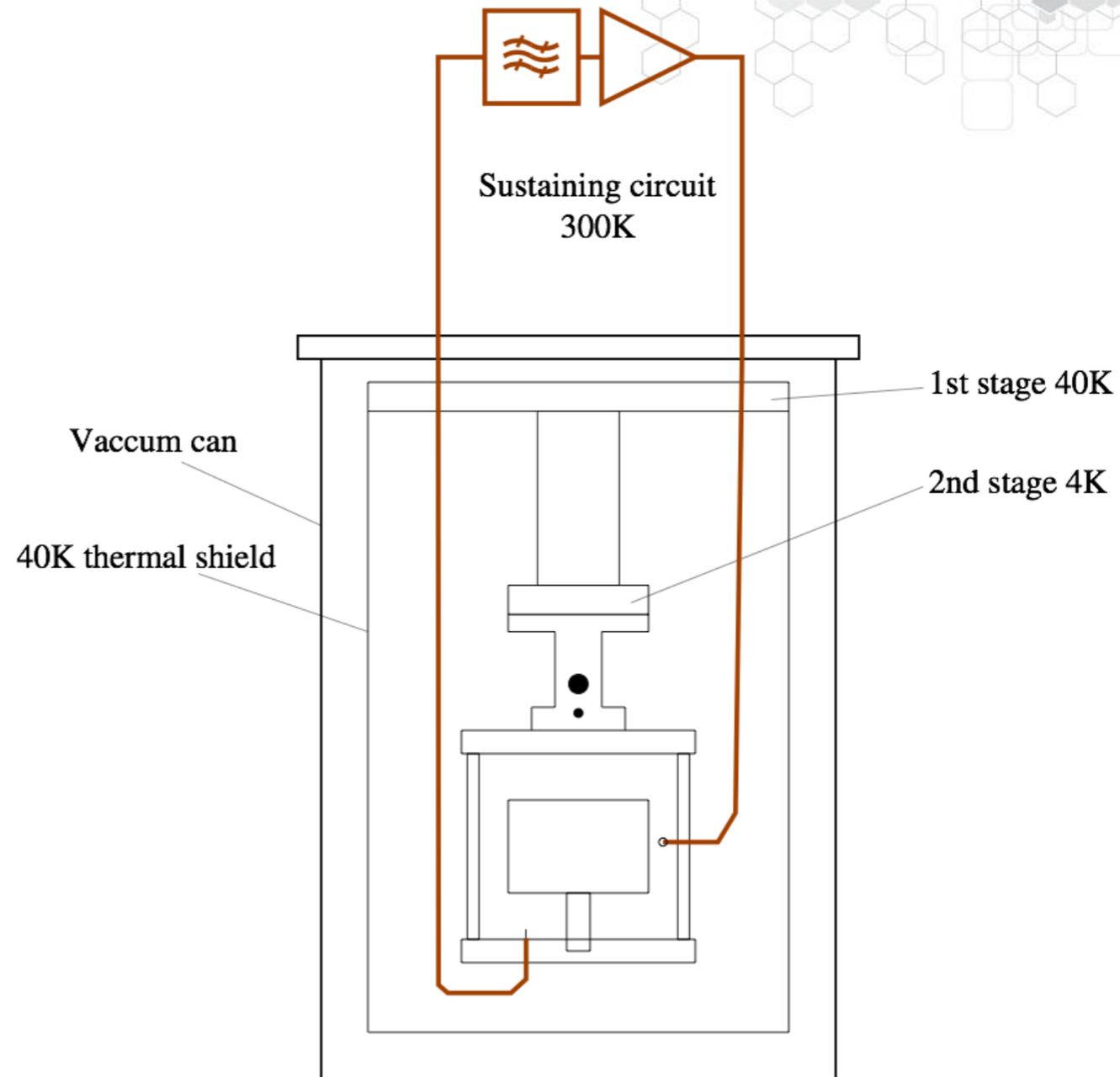
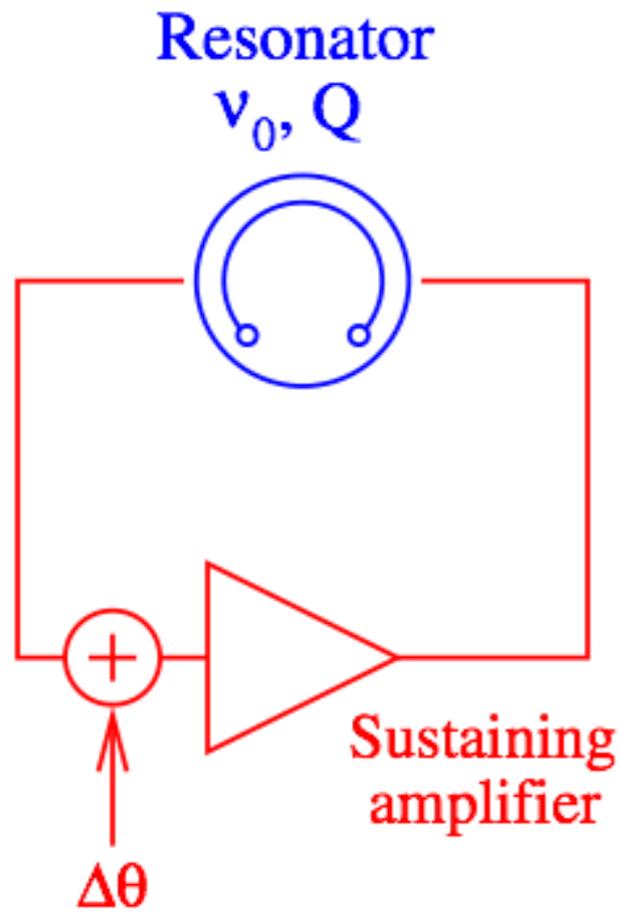
$$\frac{1}{\gamma} \frac{\Delta \nu}{\nu} \sim 3.2 \times 10^{-10} / \text{g}$$



Displacement @ 1Hz < 2 μm

Challenging for a cryocooler

# Oscillator loop



$$\frac{1}{\Delta T} \frac{\Delta \nu}{\nu} = \frac{2\pi n}{Q_L} \alpha_{Cu} \approx 2.7 \times 10^{-12} \text{K}^{-1}$$

# Pound servo

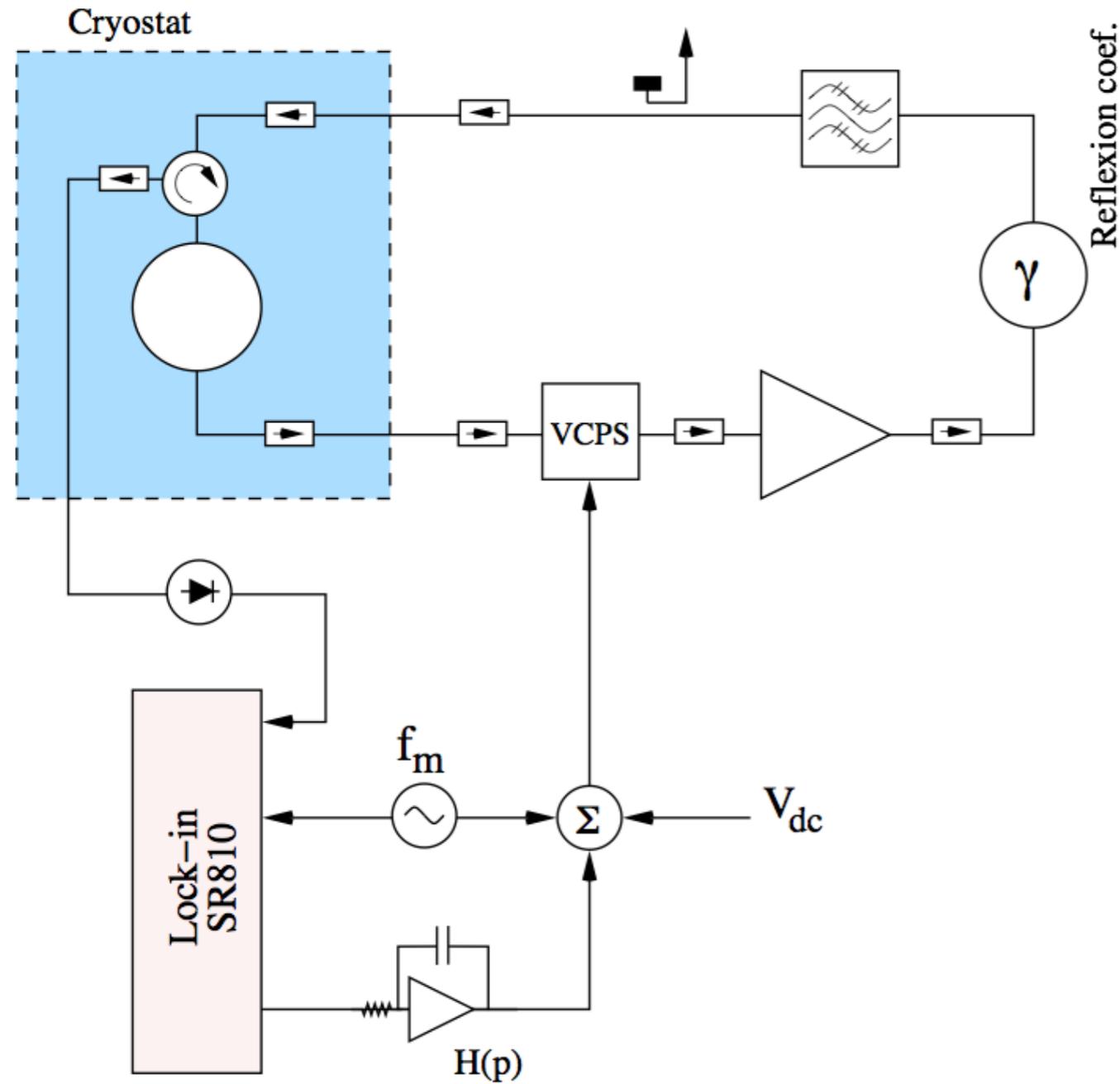
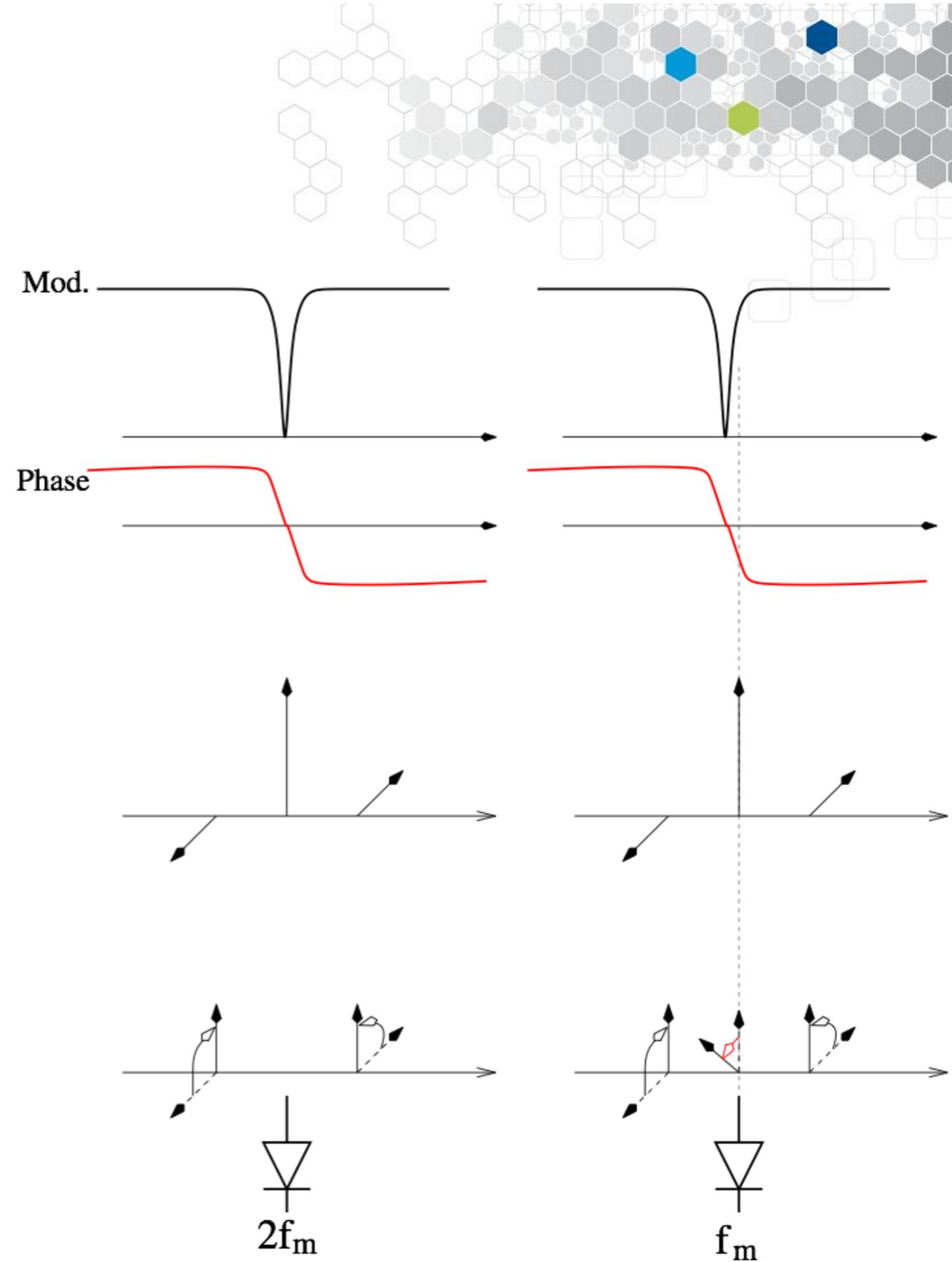


Figure 4.3: Pound servo principle

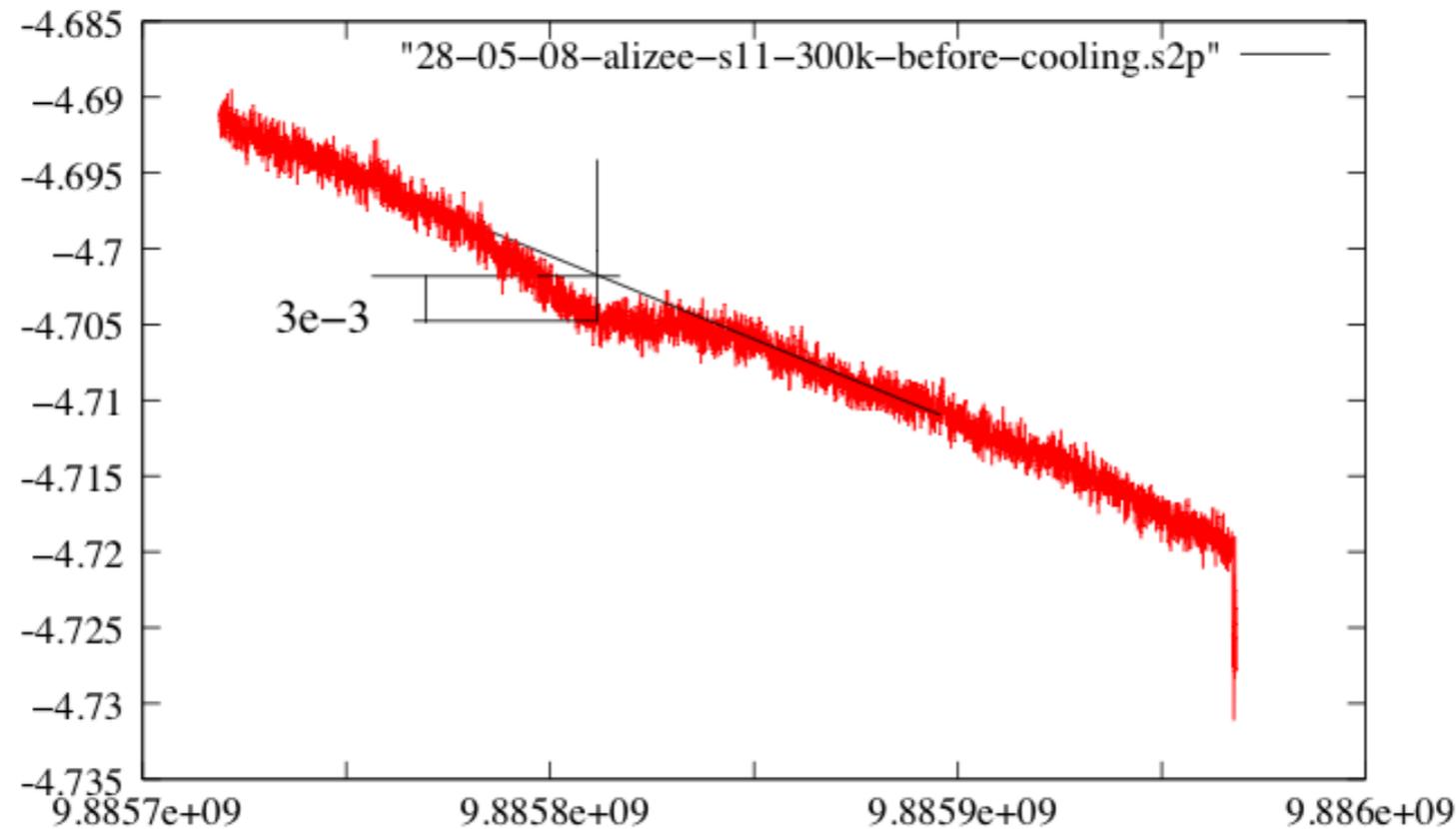
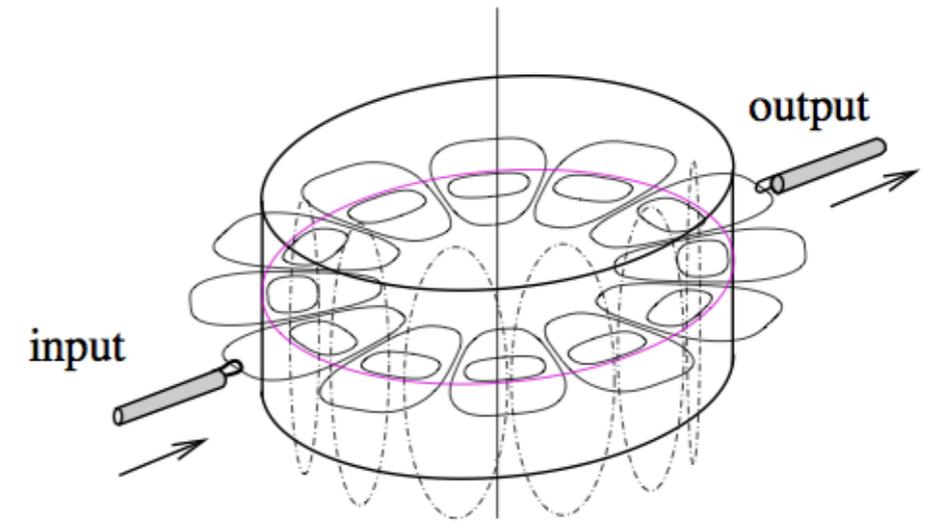




Coupling adjustment:

Pound servo optimised for  $\beta_1=1$ ,  $\beta_2 \ll 1$

$$\frac{\beta_{1_{4K}}}{\beta_{1_{300K}}} = \frac{Q_{0_{4K}}}{Q_{0_{300K}}}$$



Multiple cool downs: at last 5



vg-alizee-wgh15-s21-5k-28may08

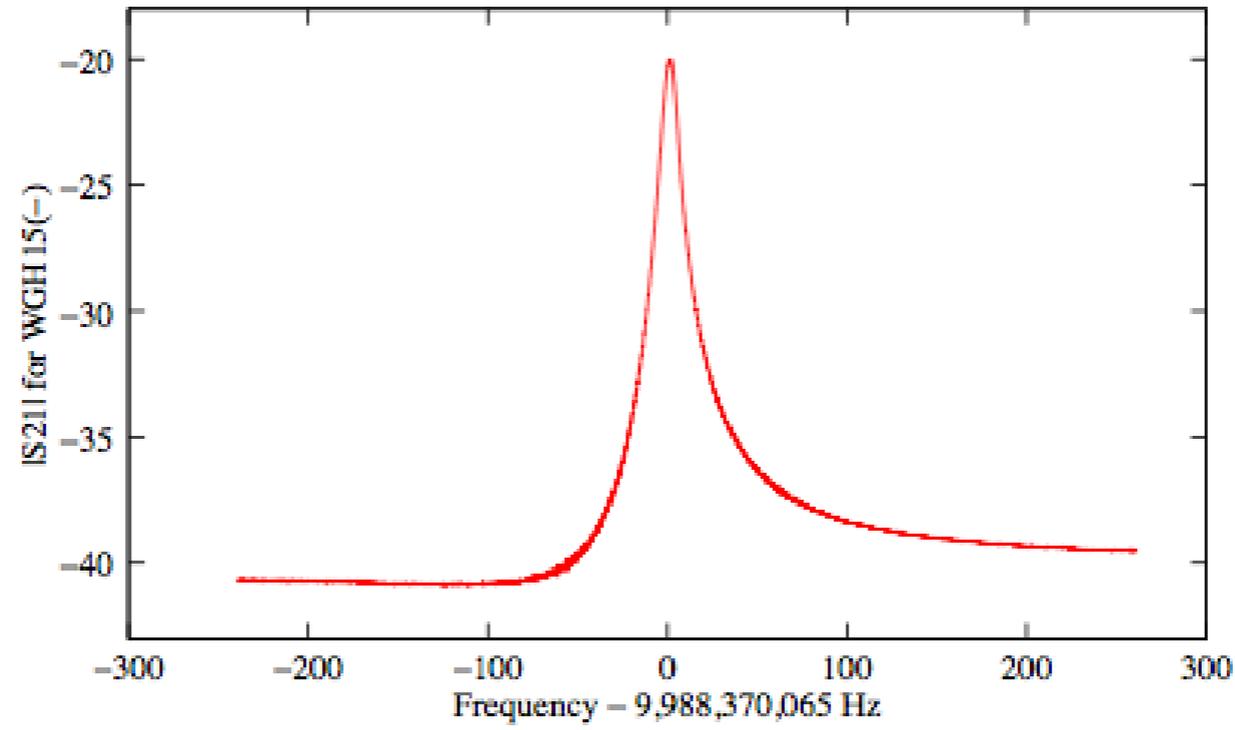
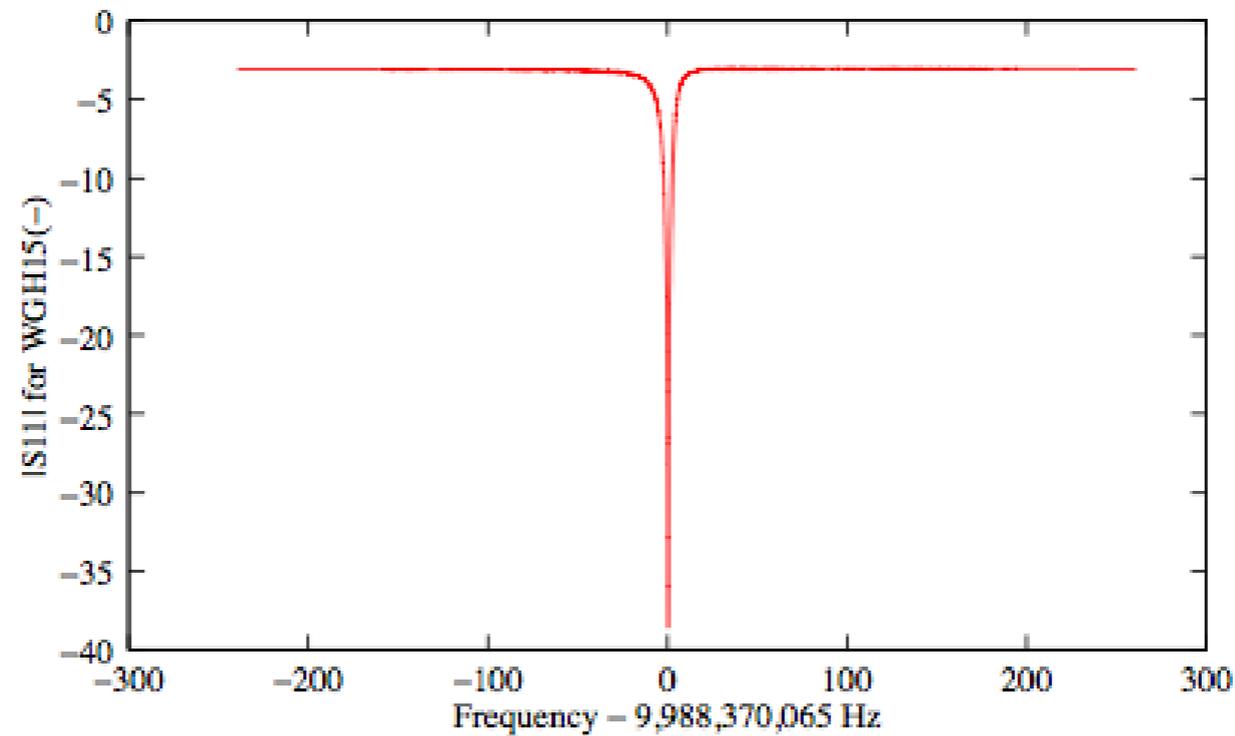
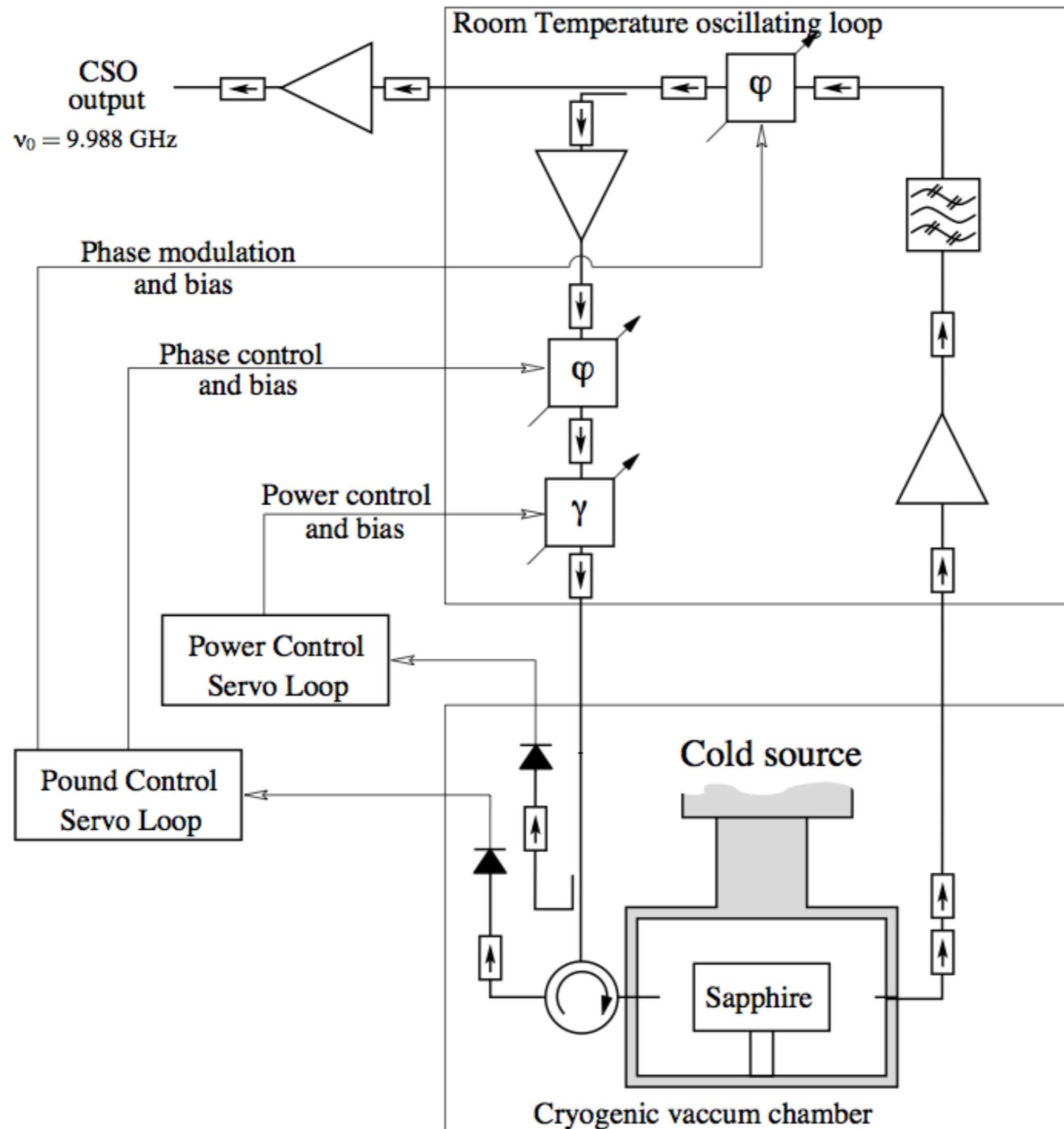
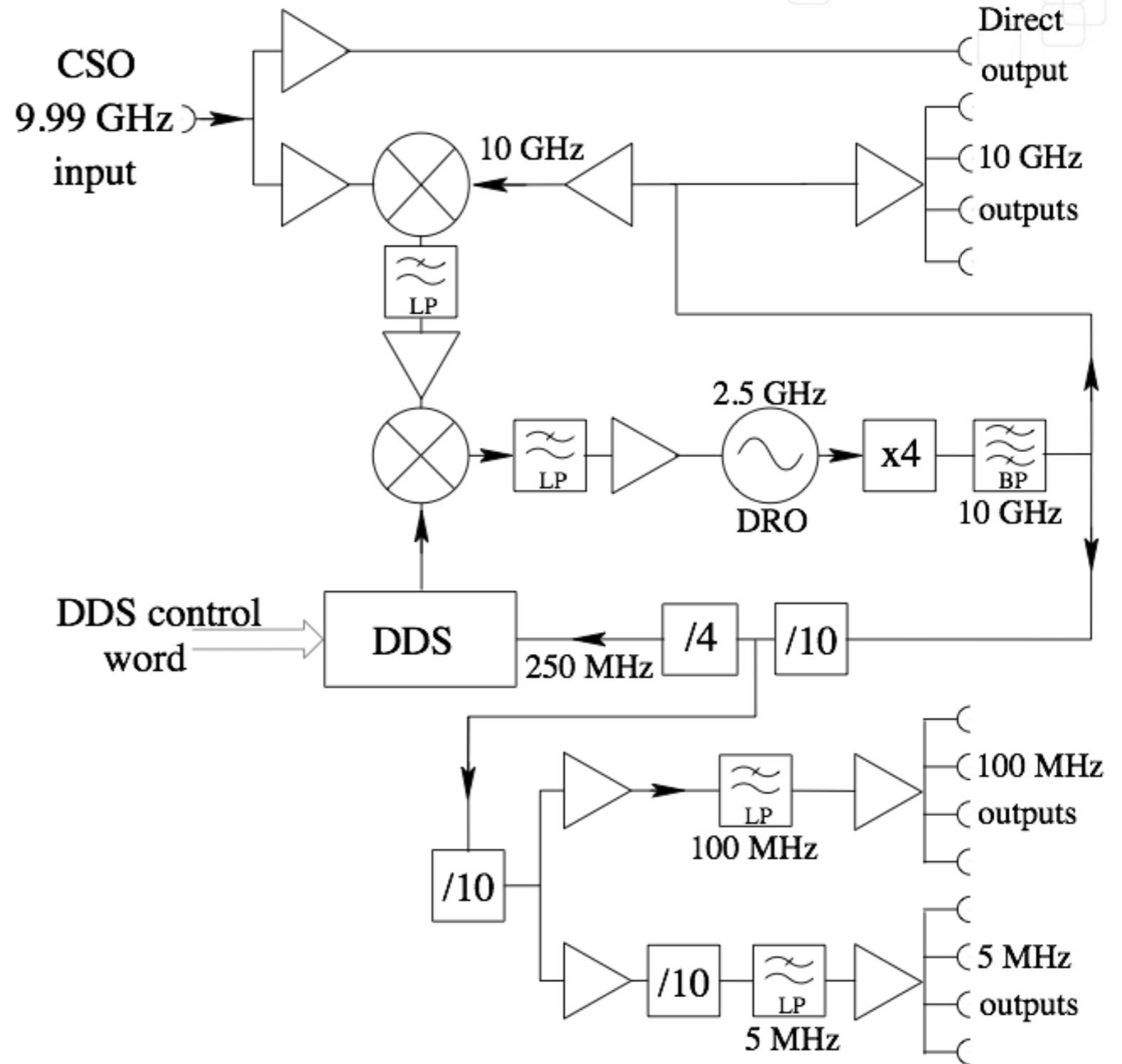


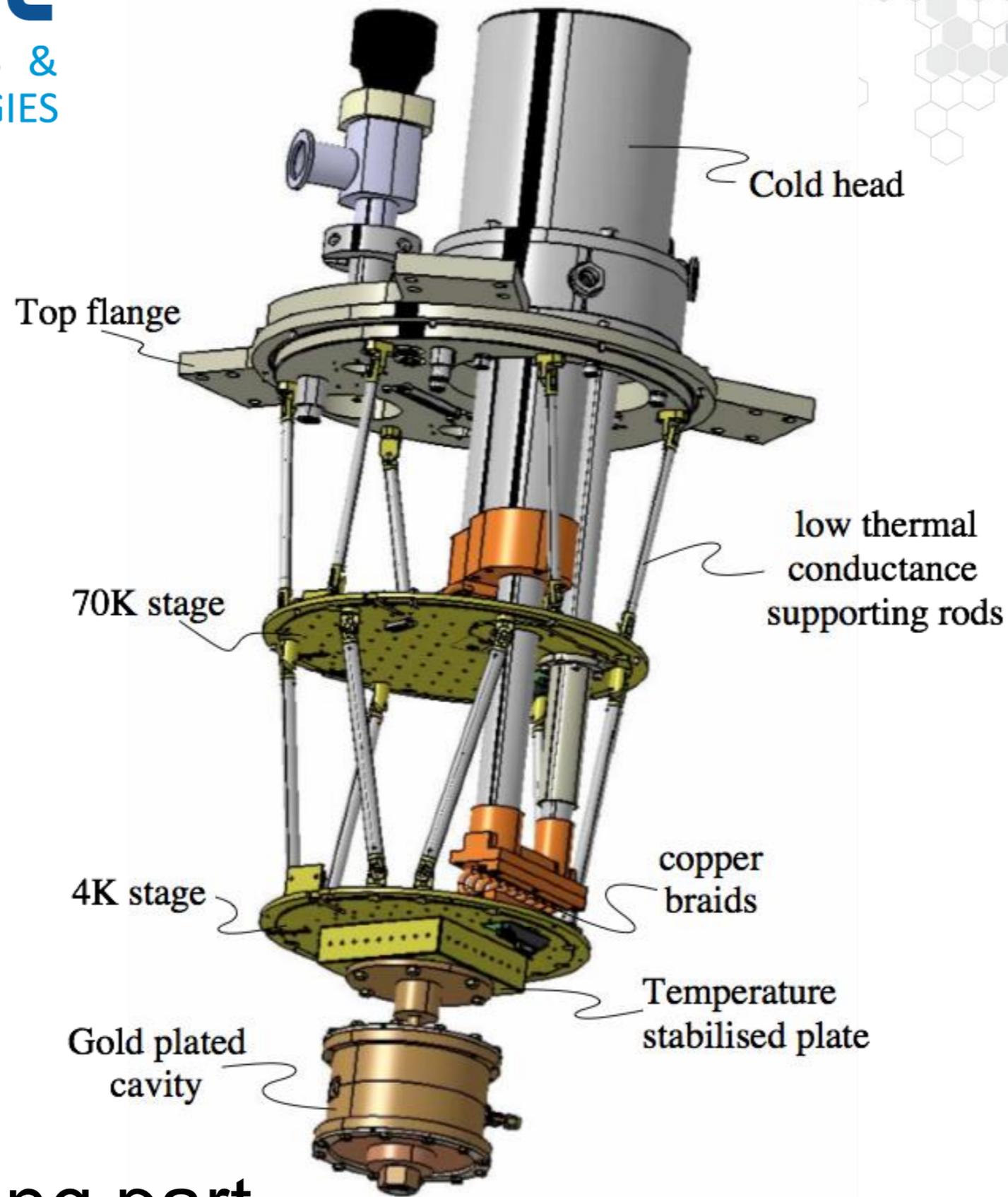
Figure 1.23: Closed cavity 5K -  $S_{21}$  c

vg-alizee-wgh15-s11-5k-28may08







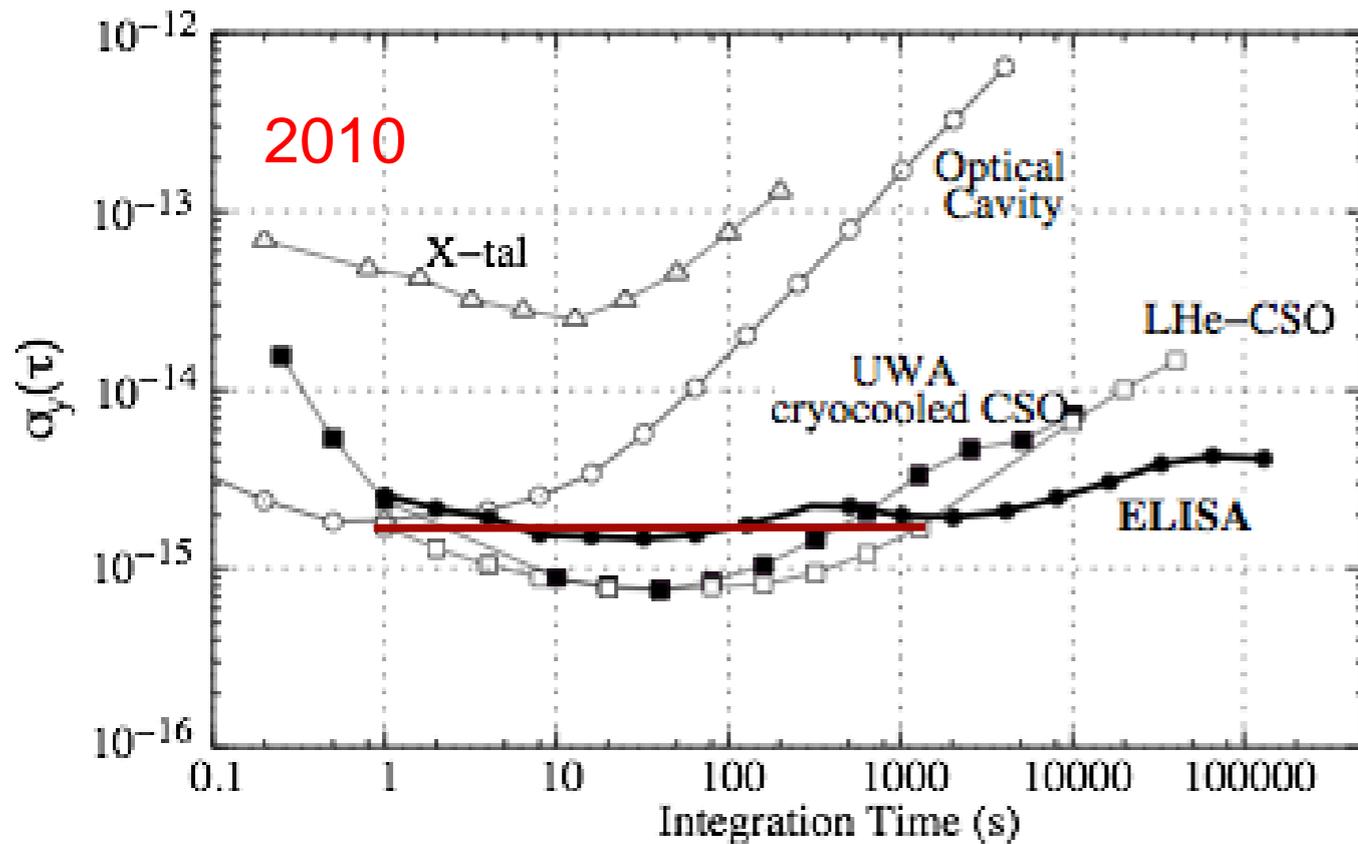


PT: no moving part

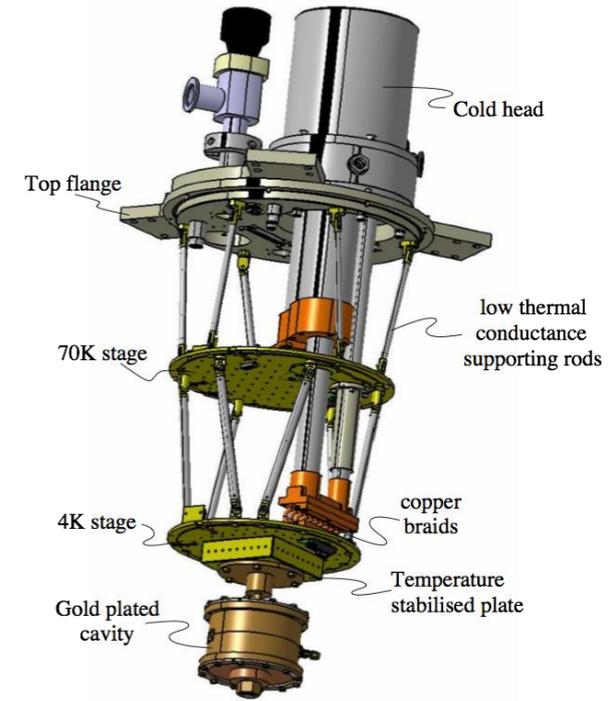
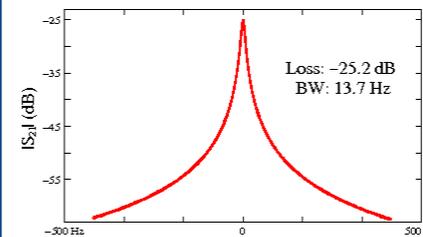
# ELISA project – CSO for the European Space Agency

Target  $3 \times 10^{-15}$  ADEV  $1s < \tau < 1000s$ , without LHe bath

- Specially designed PT Cryocooler
- 10 GHz Resonator design (to avoid complex synthesis)

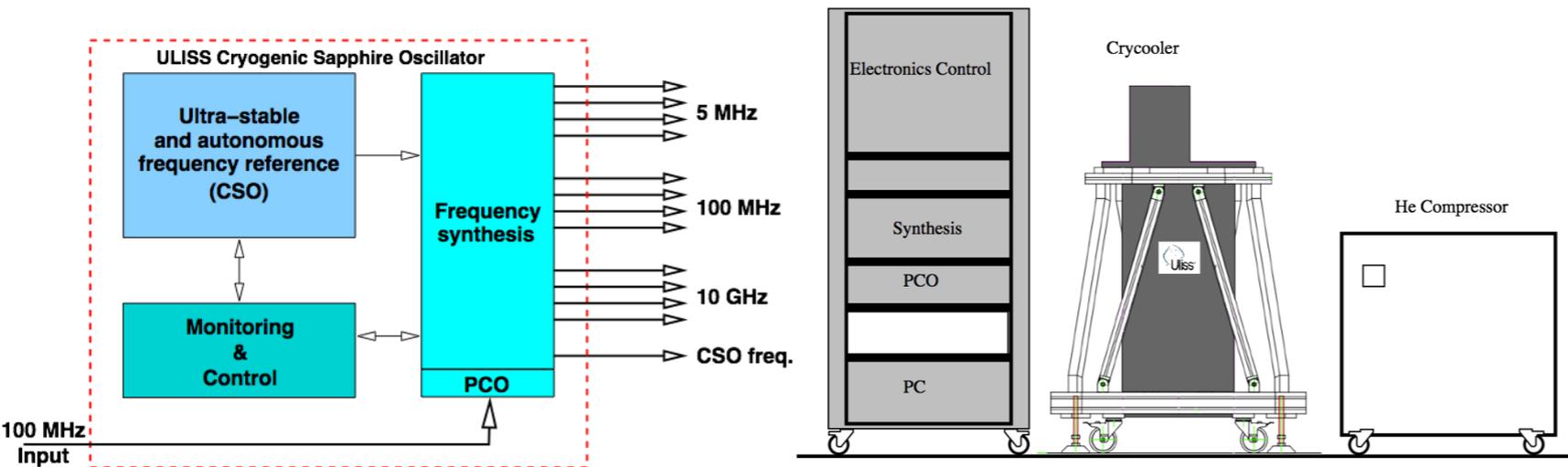


**Demonstration of a reliable CSO suitable to remote-site installation**

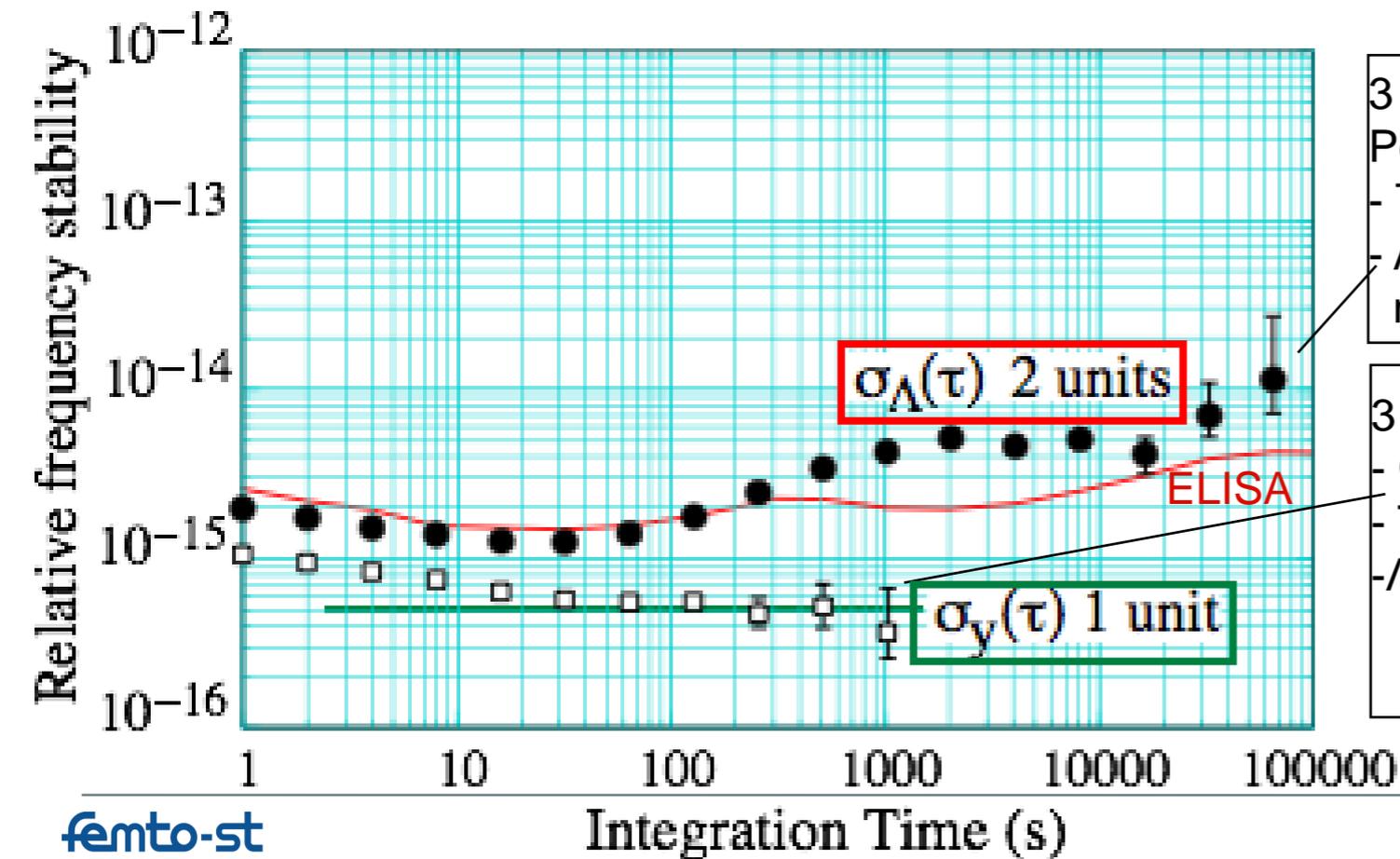


# ELISA in Malargüe, Argentina April 2012





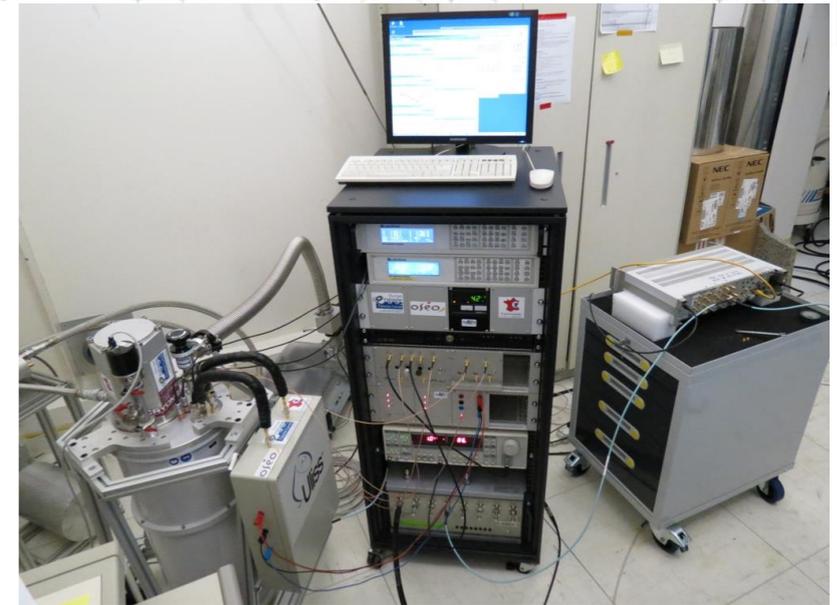
**ADEV measurement ELISA/ULISS**



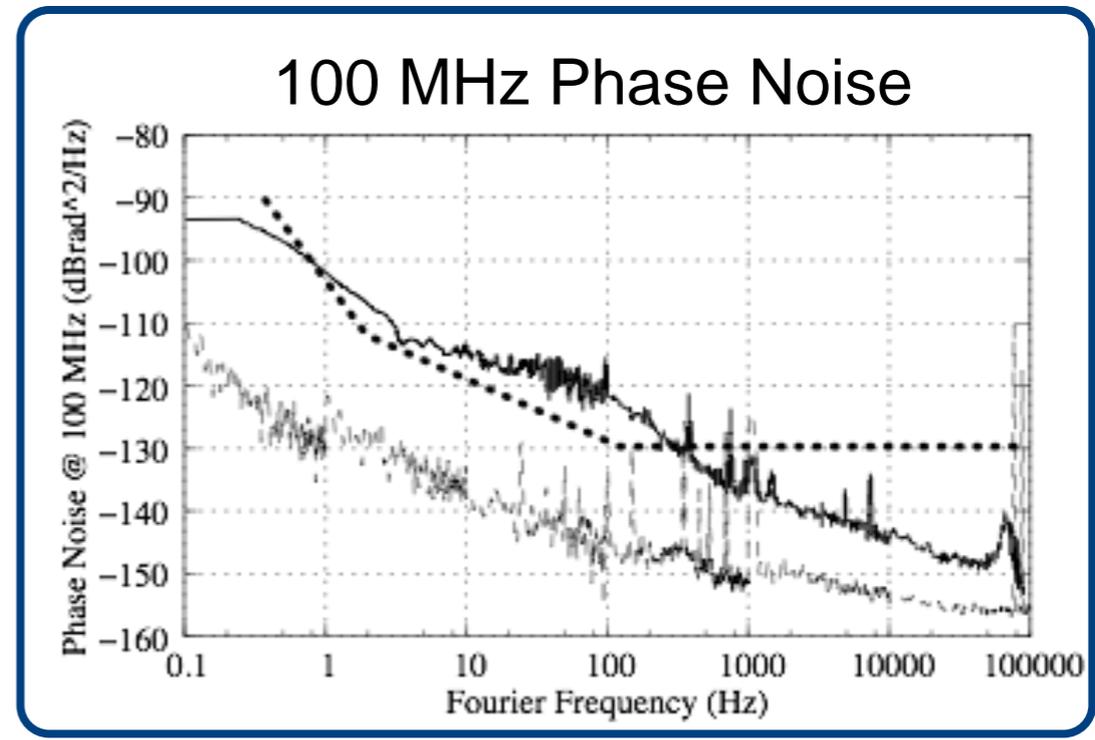
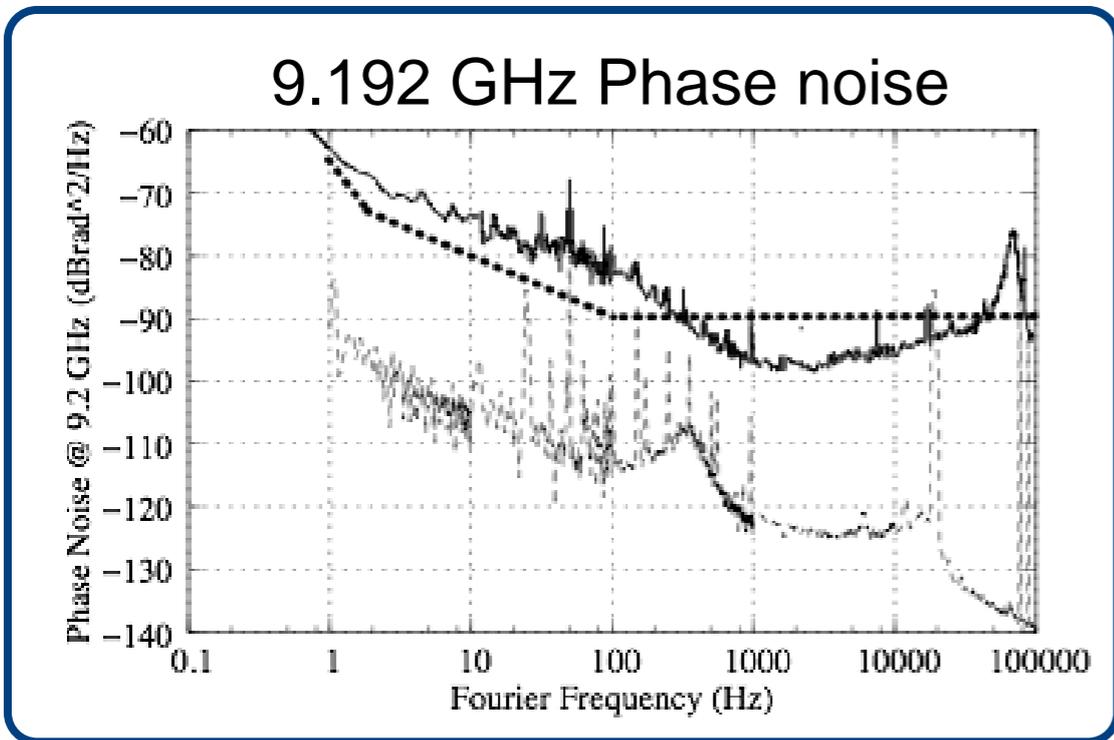
3 days measurement without post-processing  
 Perturbed environment:  
 - Technical university (ENSMM), ≥ 800 students  
 - Air conditioning still not operational during measurements

3 hours extracted from the entire data set  
 - Quiet environment, nighttime  
 - Take away 3dB for two equal units  
 -  $\Lambda$ -counter compensated: for flicker:  $\sigma_{\Lambda}(\tau) = 1.3\sigma_y(\tau)$   
**flicker floor:  $4 \times 10^{-16}$   $10 \text{ s} < \tau < 1,000 \text{ s}$**

# ULISS at CNES

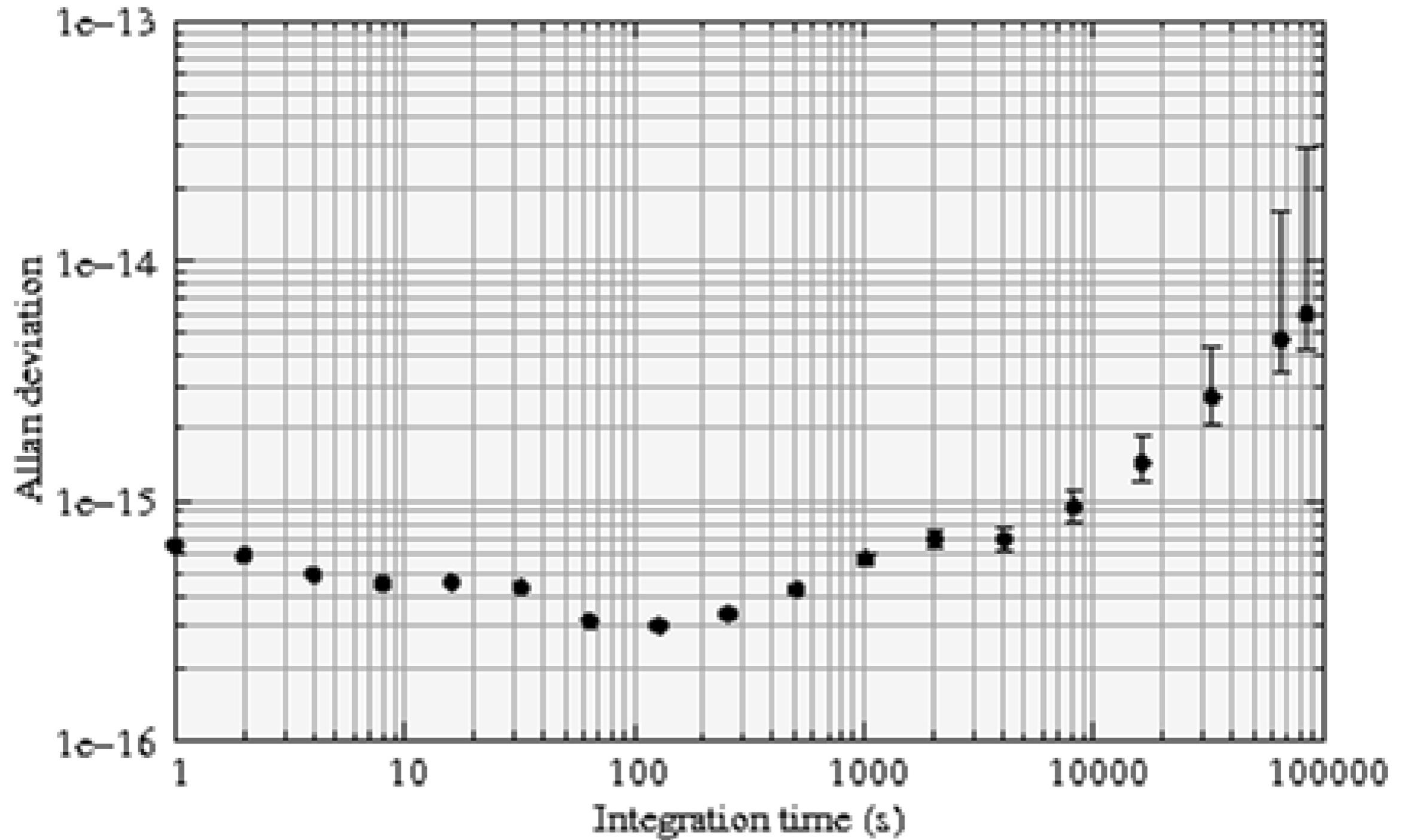


**Validate the flight prototype of the PHARAO synthesizer**



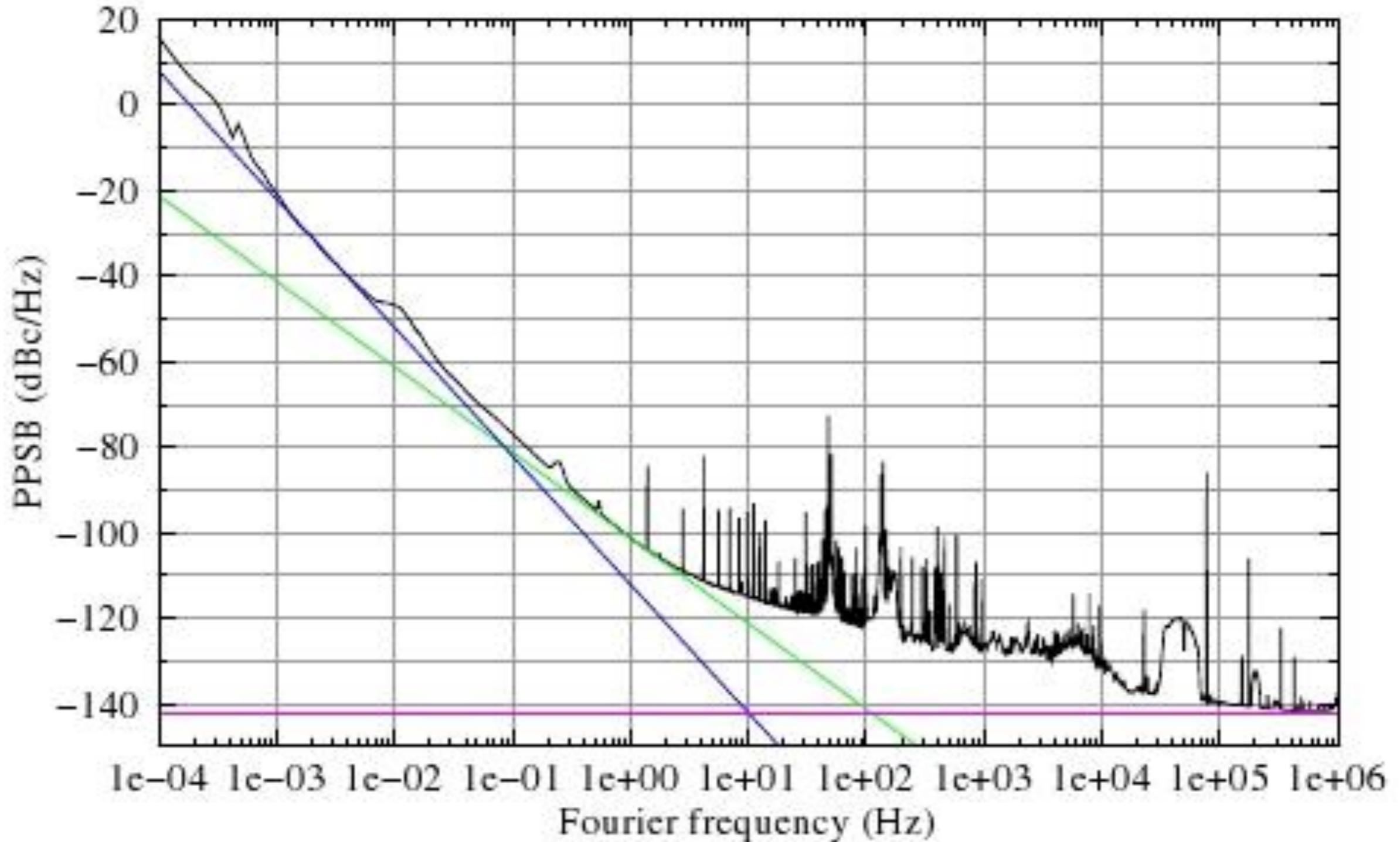


Allan deviation of one CSO





PPSD of two CSOs @9.989GHz



# OSCILLATOR-IMP projet Equipex 2012

The Oscillator-IMP project targets at being the *world-leader facility dedicated to the measurement of noise and short-term stability of oscillators and devices* in the whole radio spectrum (from MHz to THz), including microwave photonics, widely available to Agencies, to research institutions and to private companies in the spirit of global competition and economy. The scope spans from routine measurements to the research on new oscillators, components, and measurement methods.

Figure 1-2 – Block diagram of the Oscillator IMP facility

