The Abdus Salam International Centre for Theoretical Physics

Challenges and Opportunities of High Frequency Gravitational Wave Detection

14 - 16 October 2019
Trieste, Italy

Further information:
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smr3493@ictp.it

# The Schenberg Gravitational Wave Antenna: a resonant mass spherical antenna

Odylio D. Aguiar

October 14th, 2019

INPE

PROJETO GRÁVITON

GRAVITON GROUP

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

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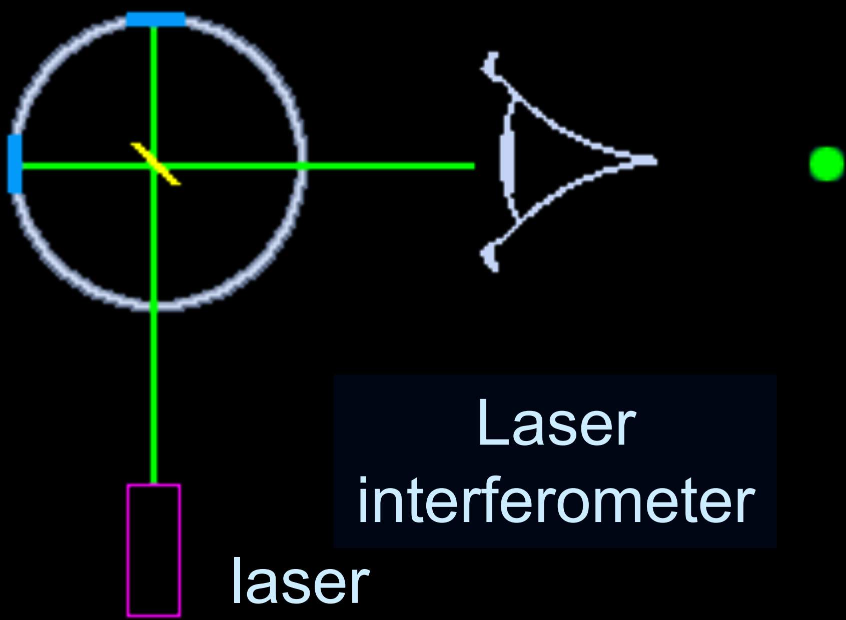
The Schenberg antenna is a resonant mass spherical antenna equipped with a set of parametric transducers for gravitational wave detection.

# Some of the techniques for gravitational wave detection

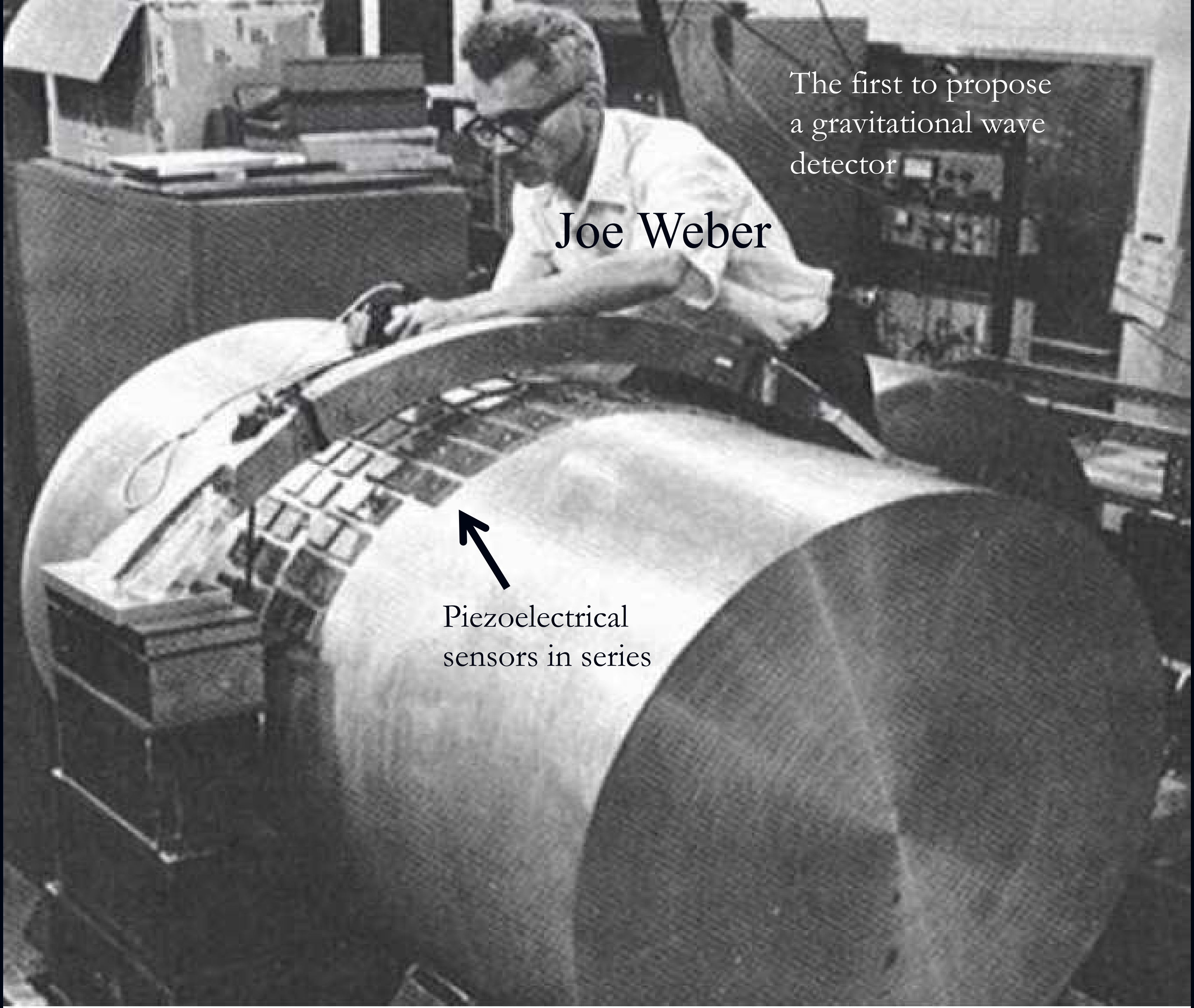



Resonant
bar

The spherical configuration has the advantage to not be blind to any direction and to determine the signal polarization and source direction

Resonant
sphere

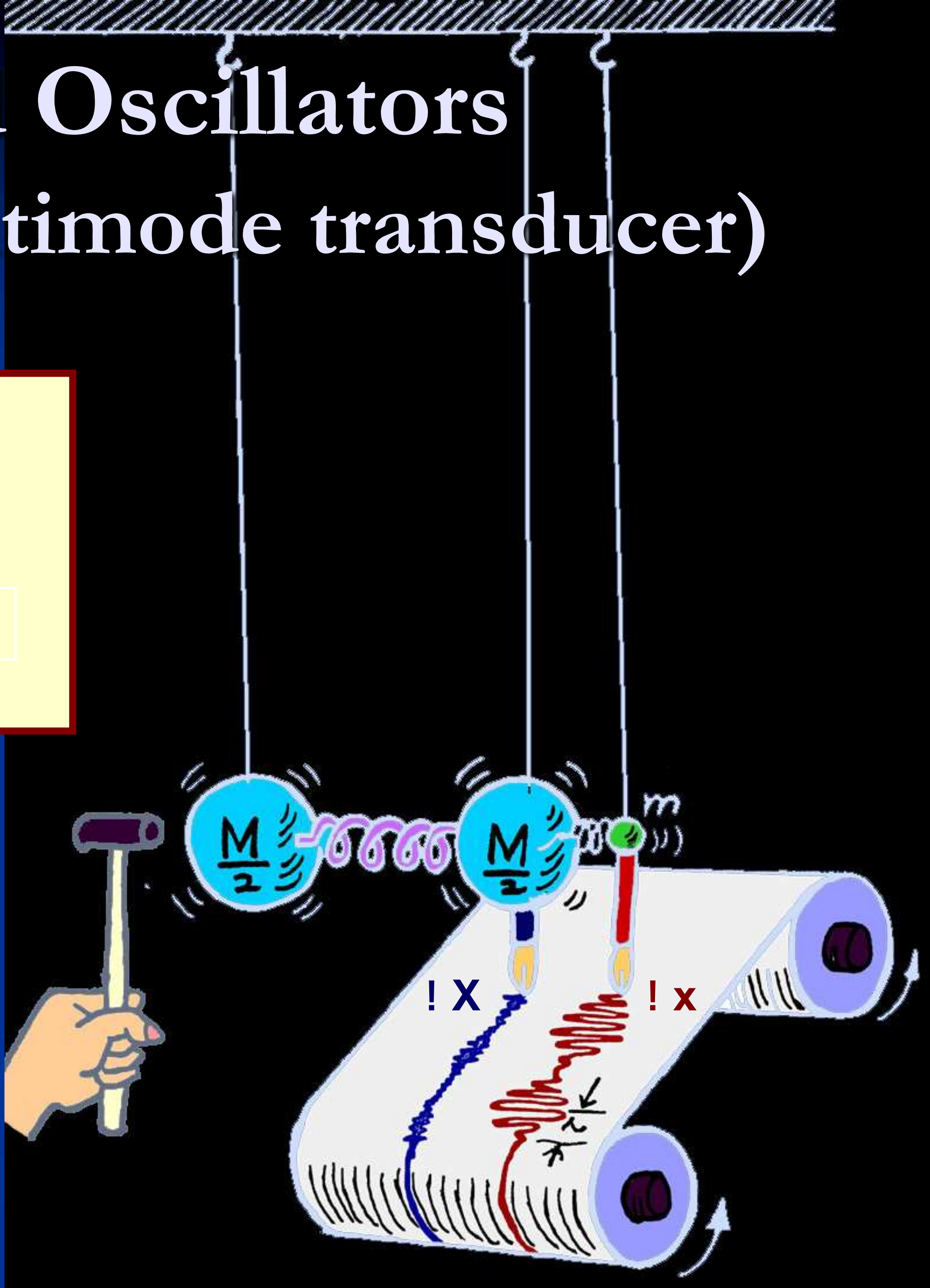
credit: Arlette de Ward


The first to propose
a gravitational wave
detector
Joe Weber
Piezoelectrical
sensors in series

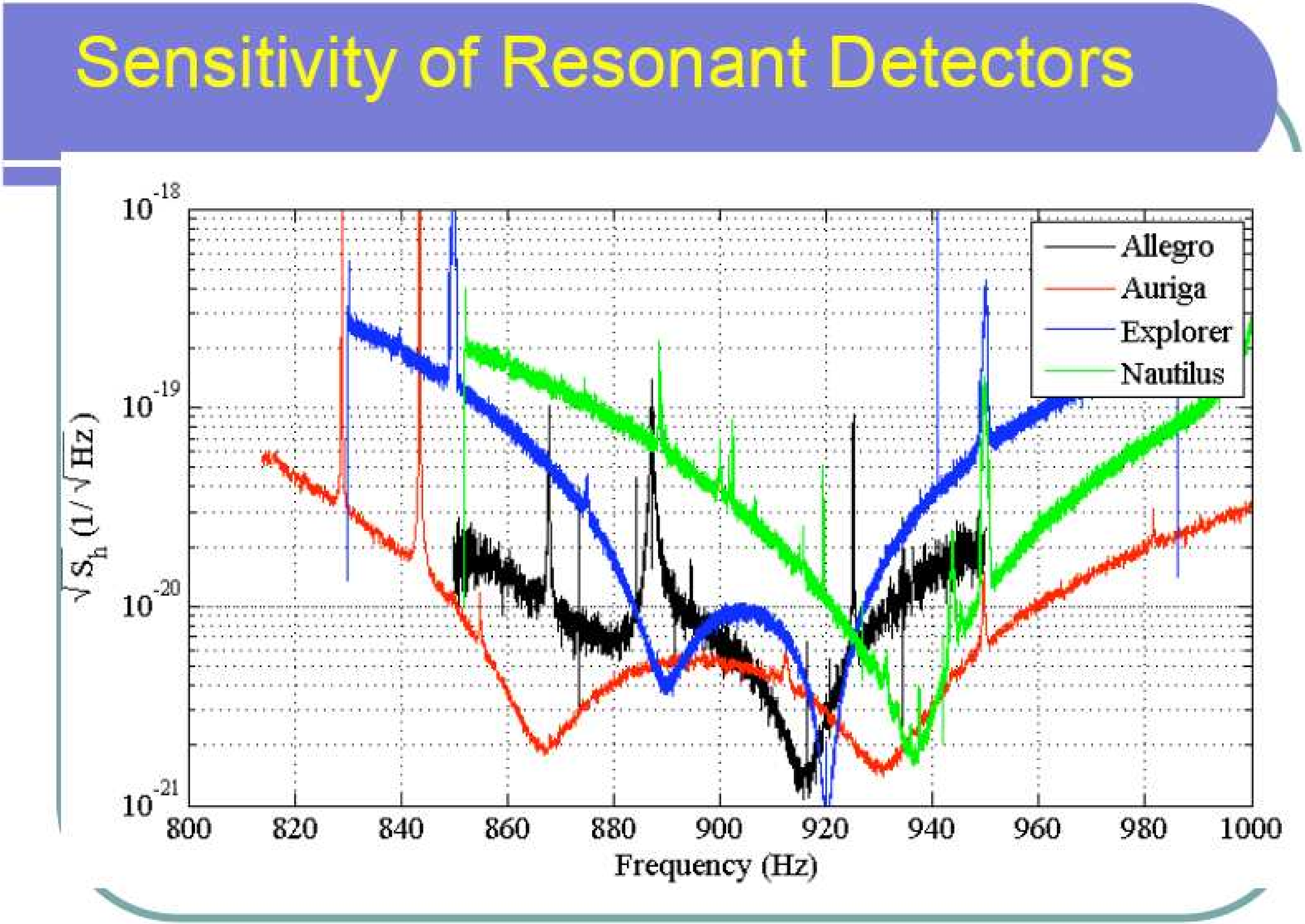
# Coupled Oscillators
## (antenna + multimode transducer)

$$\Delta x = \sqrt{\frac{M}{m}}\,\Delta X$$

Ho Jung Paik



# Sensitivity of four of the five resonant bar antennas




credit: Kostas Kokkotas

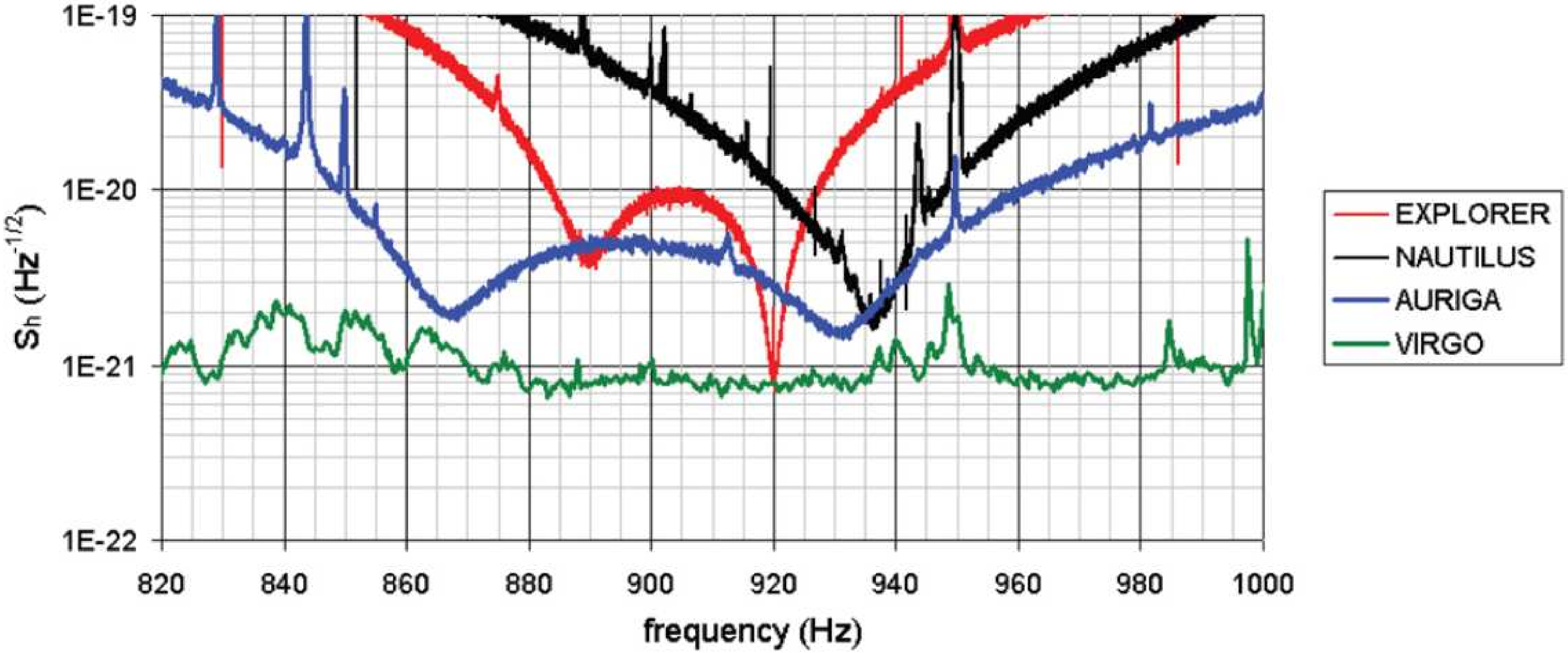
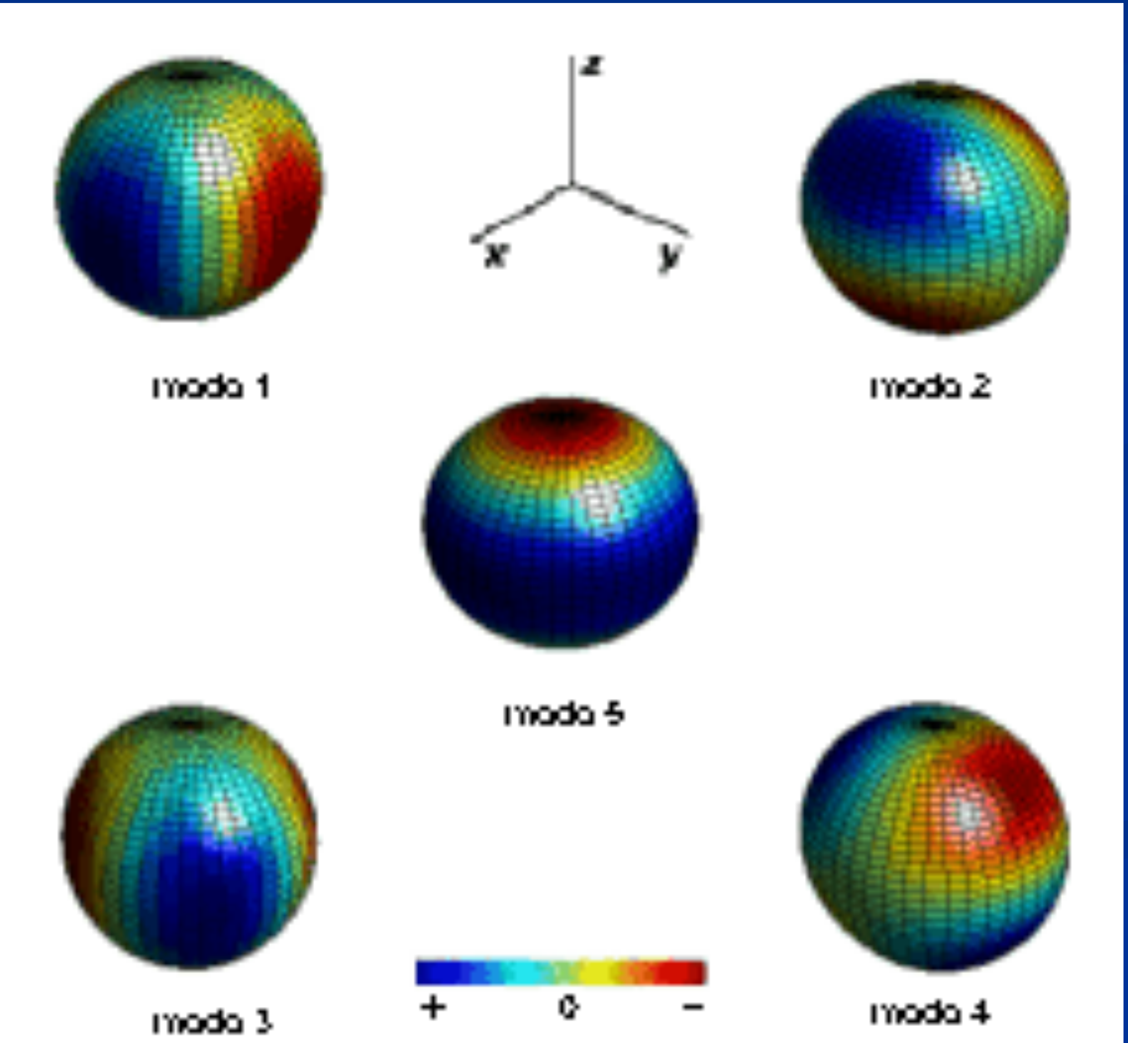



**Figure 1.** Typical spectral density of calibrated noise for the three resonant bar detectors during 2005 and for the Virgo interferometer in September 2005.

# Quadrupole modes of the a solid sphere

Spherical antennas provide more information if compared with bar antennas, because of theirs quadrupole modes



# From the output of six 6 transducers tuned to the quadrupole modes

5

" (#, $, %) = &a$_i$ (%) "$_i$ (#, $)

i

spherical harmonics

$$g_{\mu'} = ( _{\mu'} + h_{\mu'}$$

$$h_{xx} + h_{yy} + h_{zz} = 0$$

$$lh = \begin{bmatrix} h_{xx} & h_{xy} & h_{xz} \\ h_{yx} & h_{yy} & h_{yz} \\ h_{zx} & h_{zy} & h_{zz} \end{bmatrix}$$

5 independent components

Sensitivity of the spherical gravitational wave detector MiniGRAIL operating at 5 K
L. Gottardi,* A. de Waard, O. Usenko, and G. Frossati.
PHYSICAL REVIEW D 76, 102005 (2007)

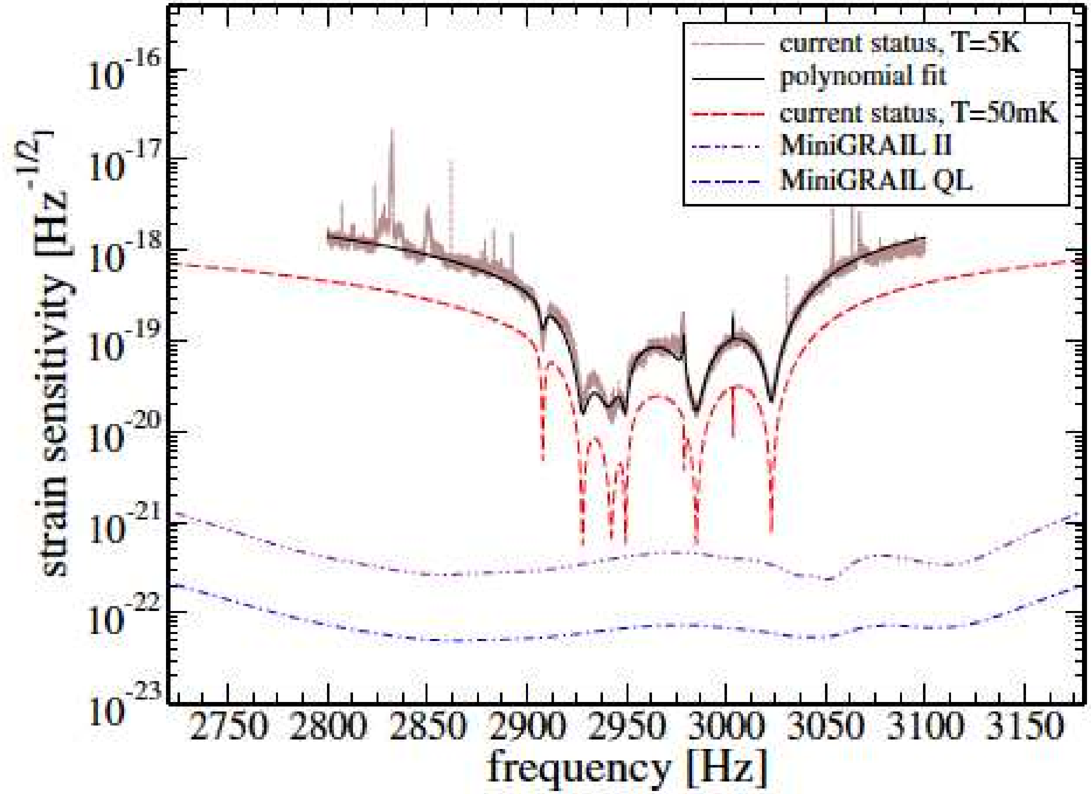
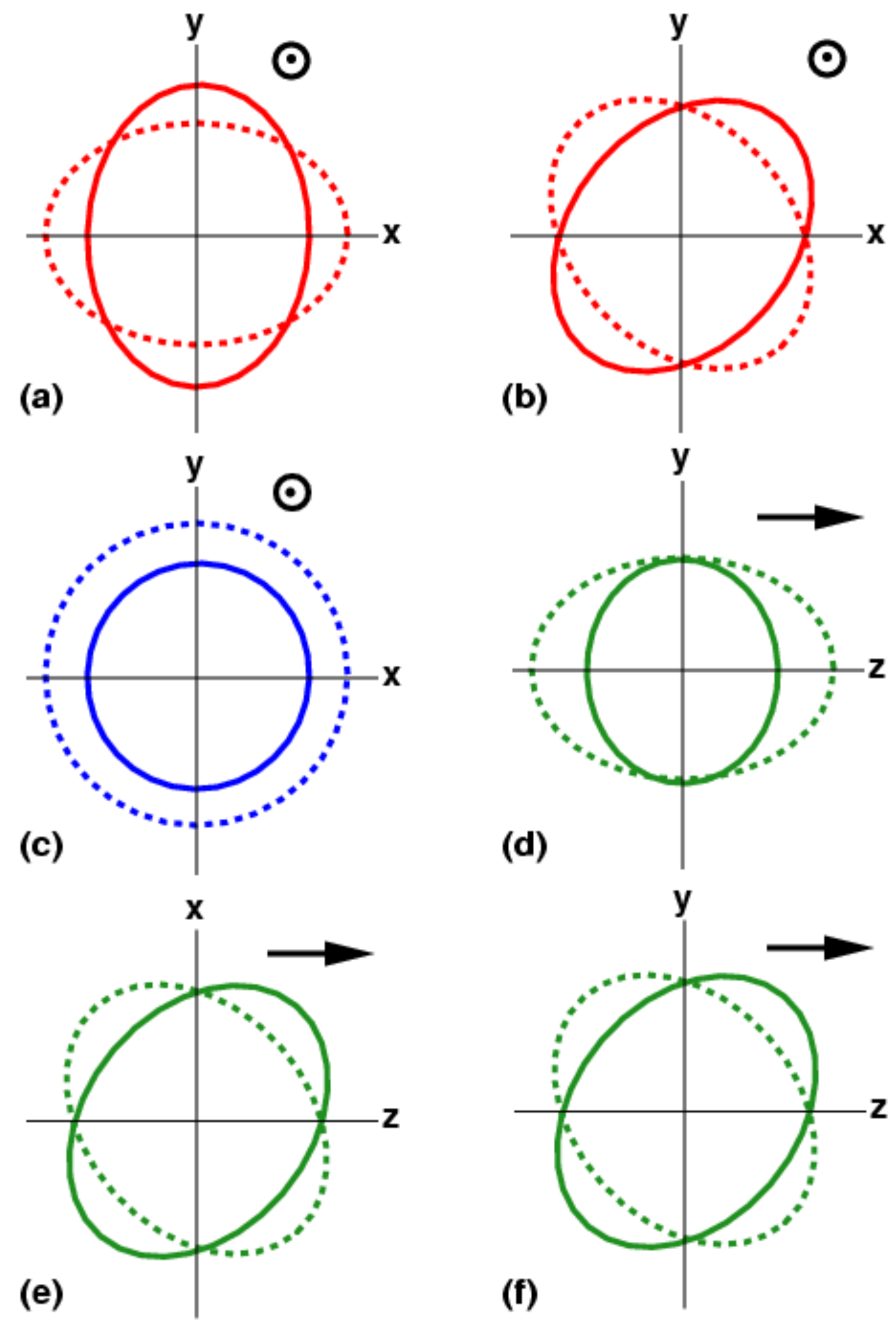
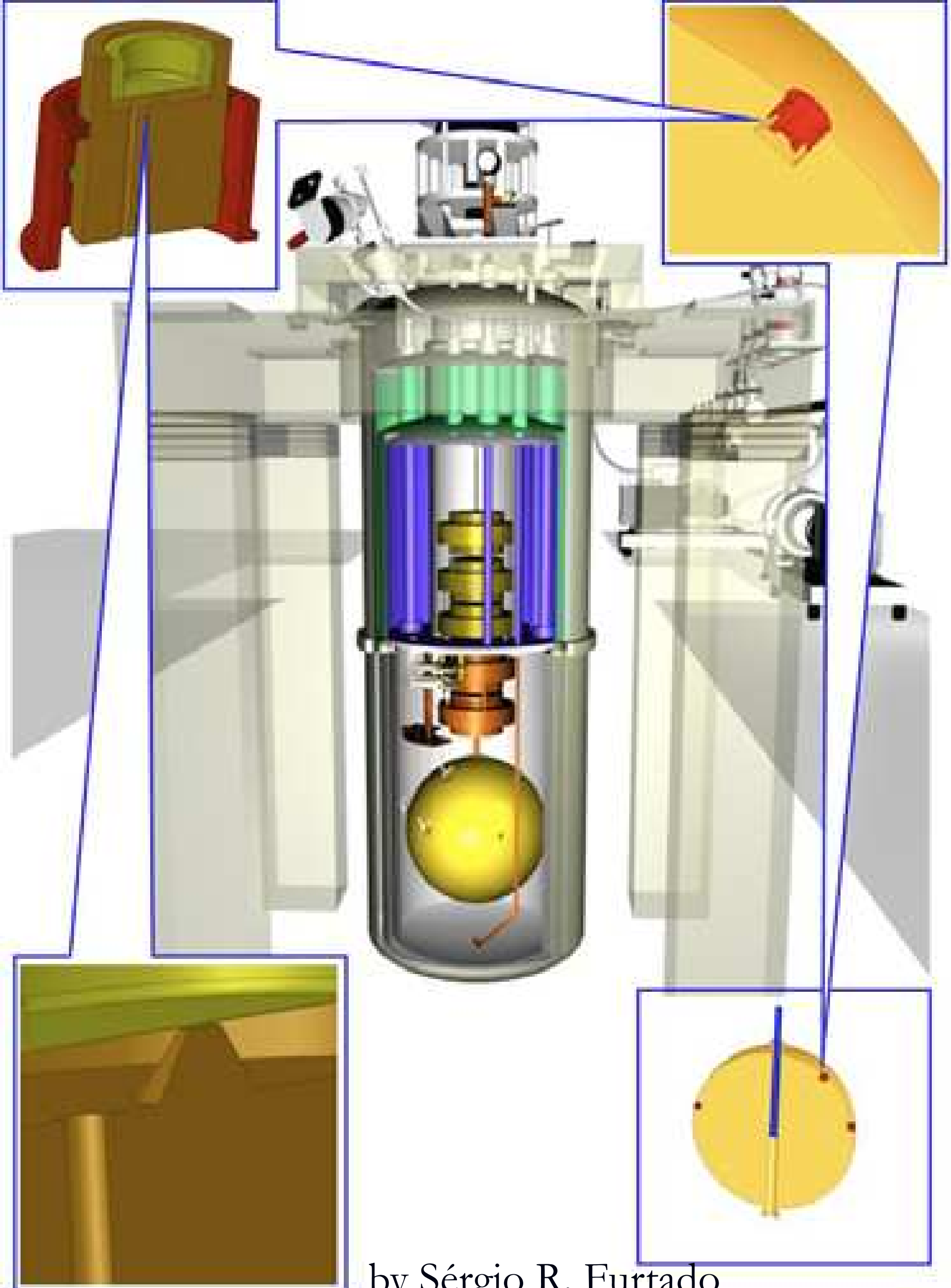



FIG. 7 (color online). The measured strain sensitivity of MiniGRAIL is shown together with the predicted sensitivity for future detector configurations. The continuous line is a polynomial fit of the measured strain sensitivity. The dashed line shows the expected sensitivity for the detector operating at $T = 50$ mK with the same three transducers configuration presented in this paper. The dot-dot-dashed line (*MiniGRAIL II*) shows the sensitivity achievable with available technology, namely $T/Q \sim 2.5 \times 10^{-8}$ K and SQUID energy resolution $E = 70\hbar$. The dot-dashed curve gives the sensitivity for a quantum limited detector (*MiniGRAIL QL*) with $T/Q \sim 1 \times 10^{-9}$ K.

-We will try to contribute with information about the wave direction and/or polarization;

-We will try to study the behavior of Schenberg in a macroscopic quantum oscillator regime.





by Sérgio R. Furtado

In the case of Schenberg, there is a two mode (at ~3.2kHz) resonant transducer coupled to the spherical antenna.

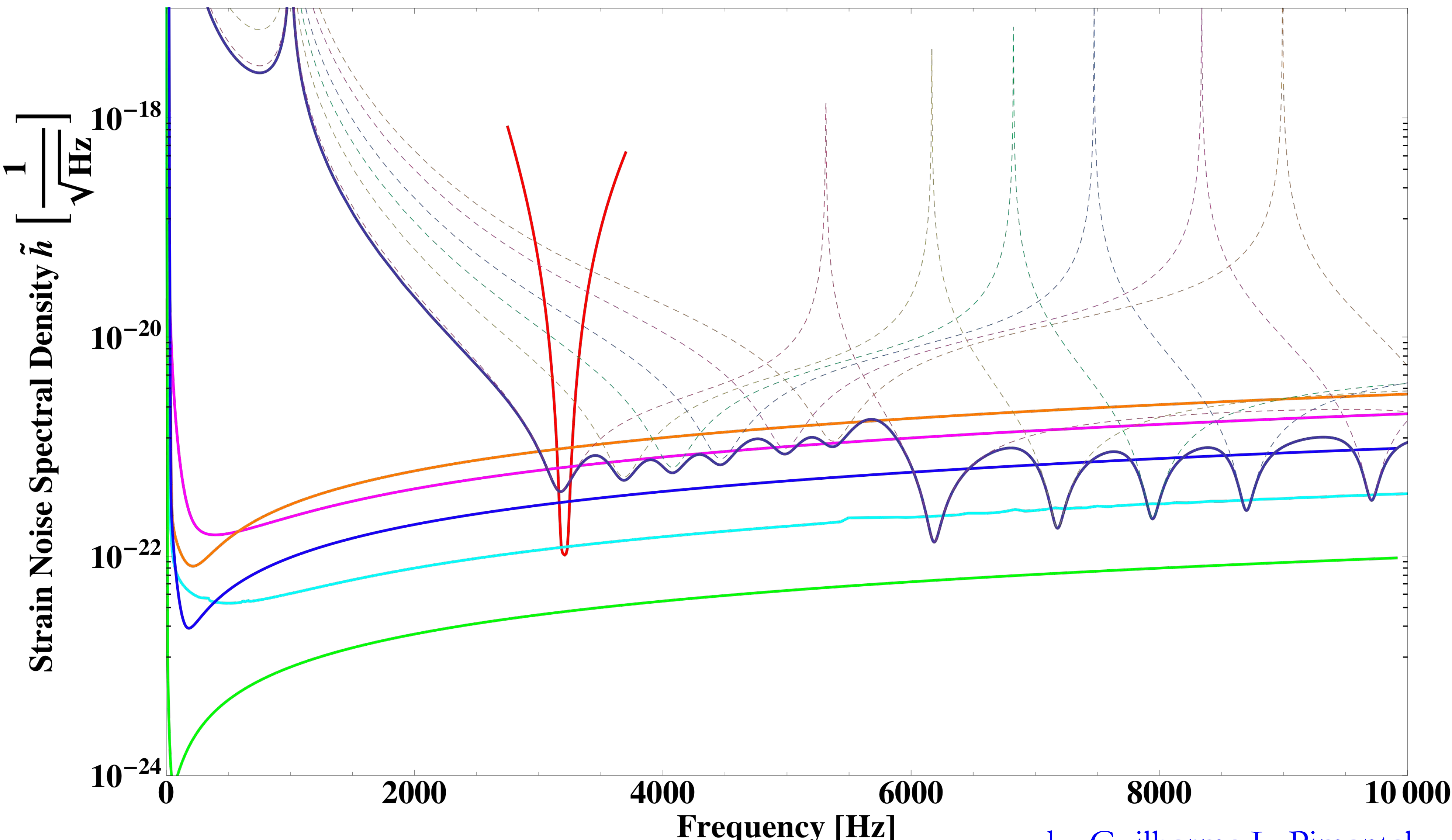
**~287 kg is the effective mass for each sphere's quadrupole mode;**

**( 5 x 287 kg = 1435 kg > 1150 kg = $M_{sphere}$ )**

**~287 kg, ~60 g and ~12 mg**
**amplitude gain ~ 5k**
**$f_o$ ~ 10 GHz**
**df/dx ~ 0.7 GHz / micron**
**→ gap of a few microns**

**or**
**non-resonant**
**with df/dx ~ 5 THz / micron**
**→ gap of 1 nanometer**

The sensitivity curve for the Schenberg broadband detector using a nanogap klystron cavity non-resonant transducer. The dashed curves represent each of the 6 spheres we chose for the array (masses: 1150 kg (Schenberg), 744 kg, 547 kg, 414 kg, 301 kg, 239 kg), the lowest frequency being Schenberg. The V-shaped red curve is Schenberg with its usual configuration operating at dilution fridge temperatures ( 10 mK). Interferometer curves are also plotted: advanced LIGO (green), LIGO (blue), VIRGO (light blue), TAMA300 (pink) and GEO600 (orange). All of these are project curves, not actual data.




by Guilherme L. Pimentel

1988 → Warren Johnson (LSU) started to revive Forward's (1971) and Paik & Wagoner's (1976) idea of a resonant spherical antenna;

1990 → Warren involved Stephen Merkowitz in this study;

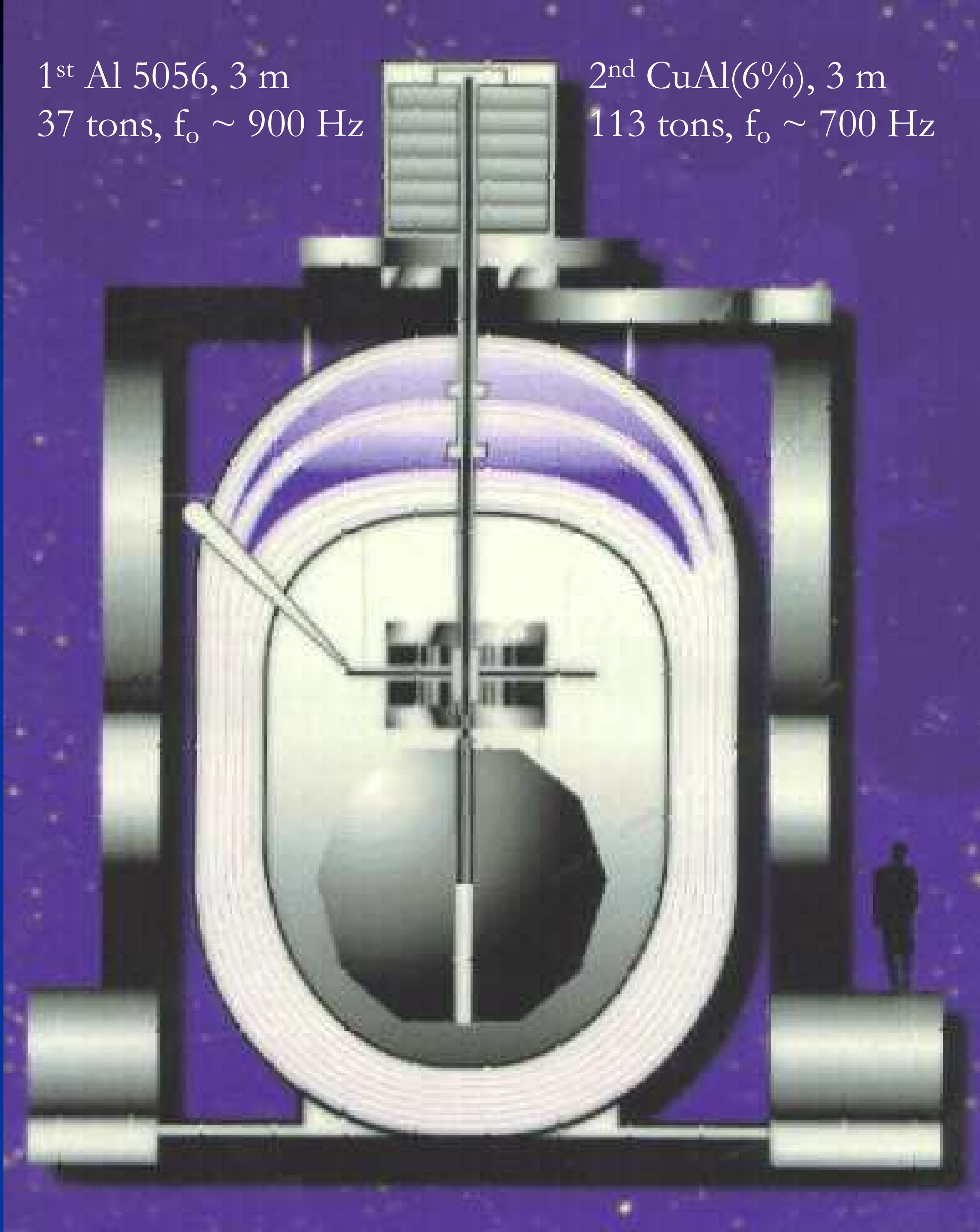
1990 → I finished my Ph.D. at LSU;

1993 → Frossati joined the field;

2000 → Schenberg antenna (construction started).

Massive detectors with spherical geometry

GRAVITON Project (Brasil) 1991



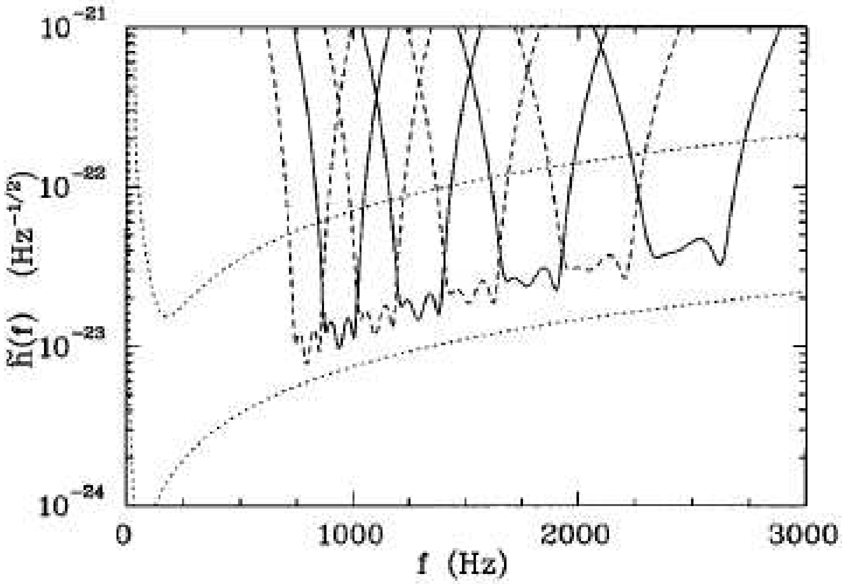



FIG. 1. The strain spectrum of the eight spherical antennas in the lowest quadrupole mode, shown with solid and dashed lines. The different line styles have no significance other than to differentiate the separate strain spectra. The upper dotted line shows the strain spectrum for the first LIGO interferometer and the lower dotted line shows the strain spectrum for the advanced LIGO interferometer, for reference. The spherical antennas, each with a sensitivty about 3 times the standard quantum limit, are more sensitive than the first LIGO interferometers in a bandwidth of about 100 to 300 Hz each and together span a total bandwidth from 750 to 2700 Hz. In this band, the spherical antennas are a little less sensitive than the advanced LIGO interferometers.

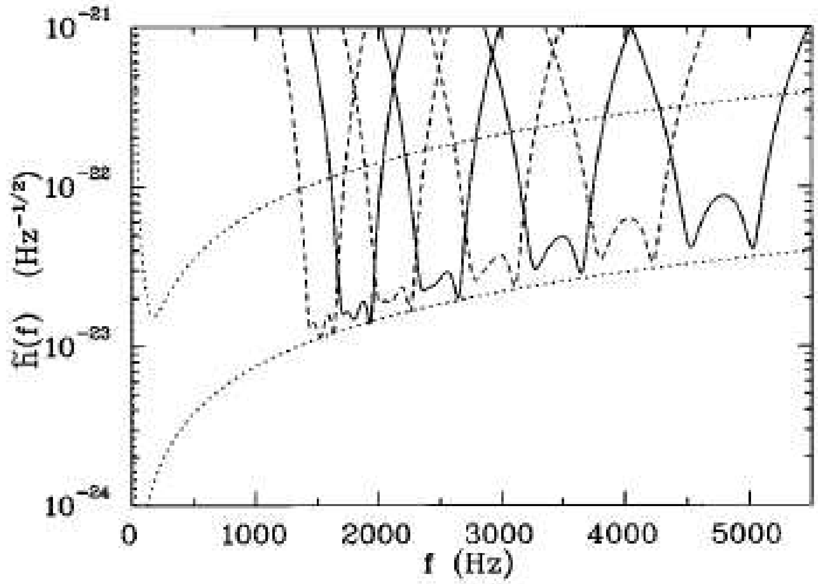



FIG. 2. The strain spectrum of the eight spherical antennas in the first excited quadrupole mode, shown with solid and dashed lines. The different line styles have no significance other than to differentiate the separate strain spectra. The upper dotted line shows the strain spectrum for the first LIGO interferometer and the lower dotted line shows the strain spectrum for the advanced LIGO interferometer, for reference. The spherical antennas, each with a sensitivity about 3 times the standard quantum limit, are more sensitive than the first LIGO interferometers in a bandwidth of about 200 to 600 Hz each and together span a total bandwidth from 1350 to 5100 Hz. In this band, the spherical antennas are about equal to the sensitivity of the advanced LIGO interferometers.

Gregory M. Harry, Thomas R. Stevenson, and Ho Jung Paik. Detectability of gravitational wave events by spherical resonant-mass antennas. Phys. Rev. D **54**, 2409, (1996)

al Wave Detectors
Interferometric
Resonant-Mass
LISA
MINIGRAIL
GA
US
TAMA
LCGT
RG
AIGO
NIOBE
MiniGRAIL
Netherlands
Mario Schenberg,
Brazil
(FAPESP)
ational wave research

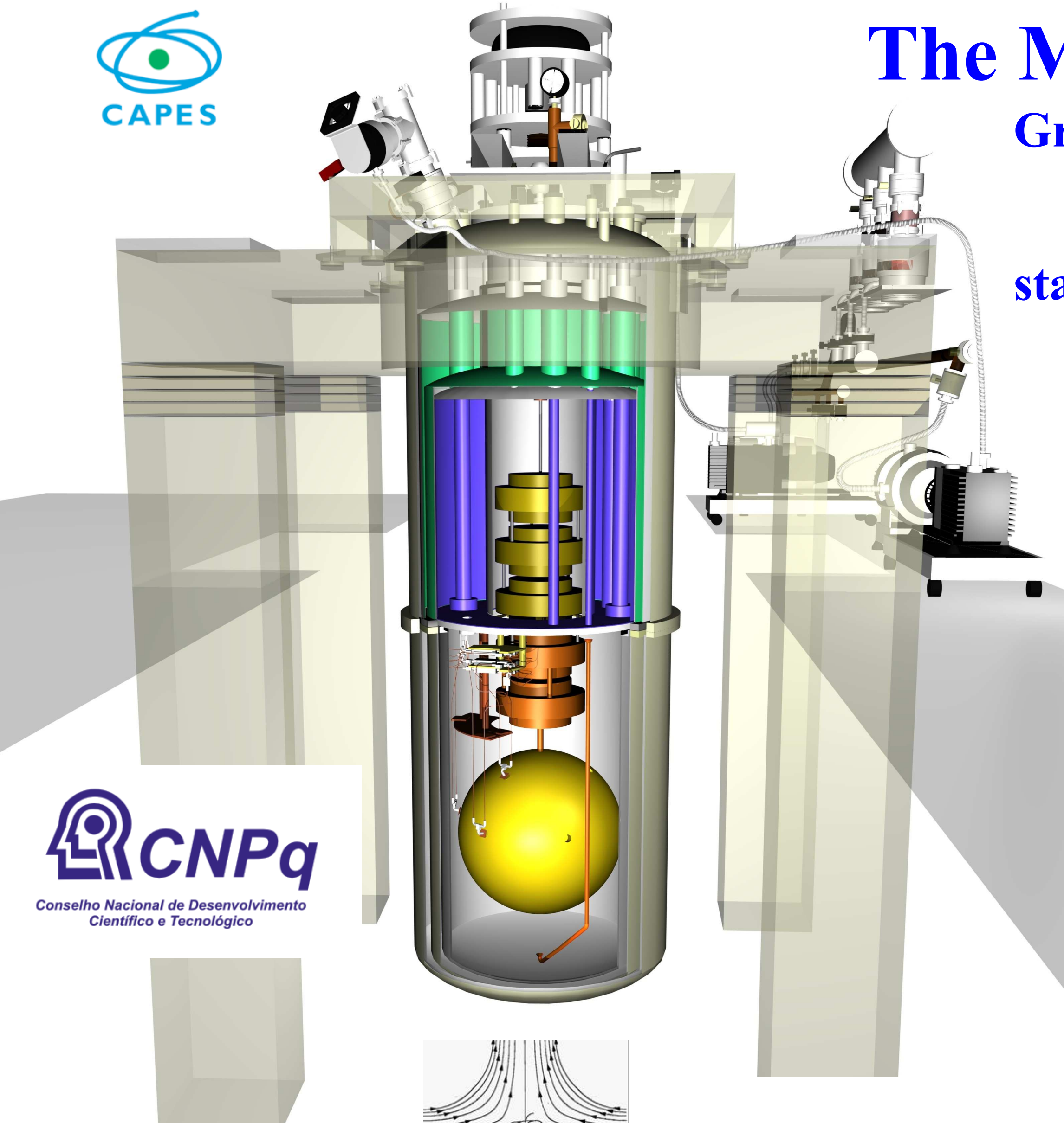
# The Mario SCHENBERG

## Gravitational Wave Detector

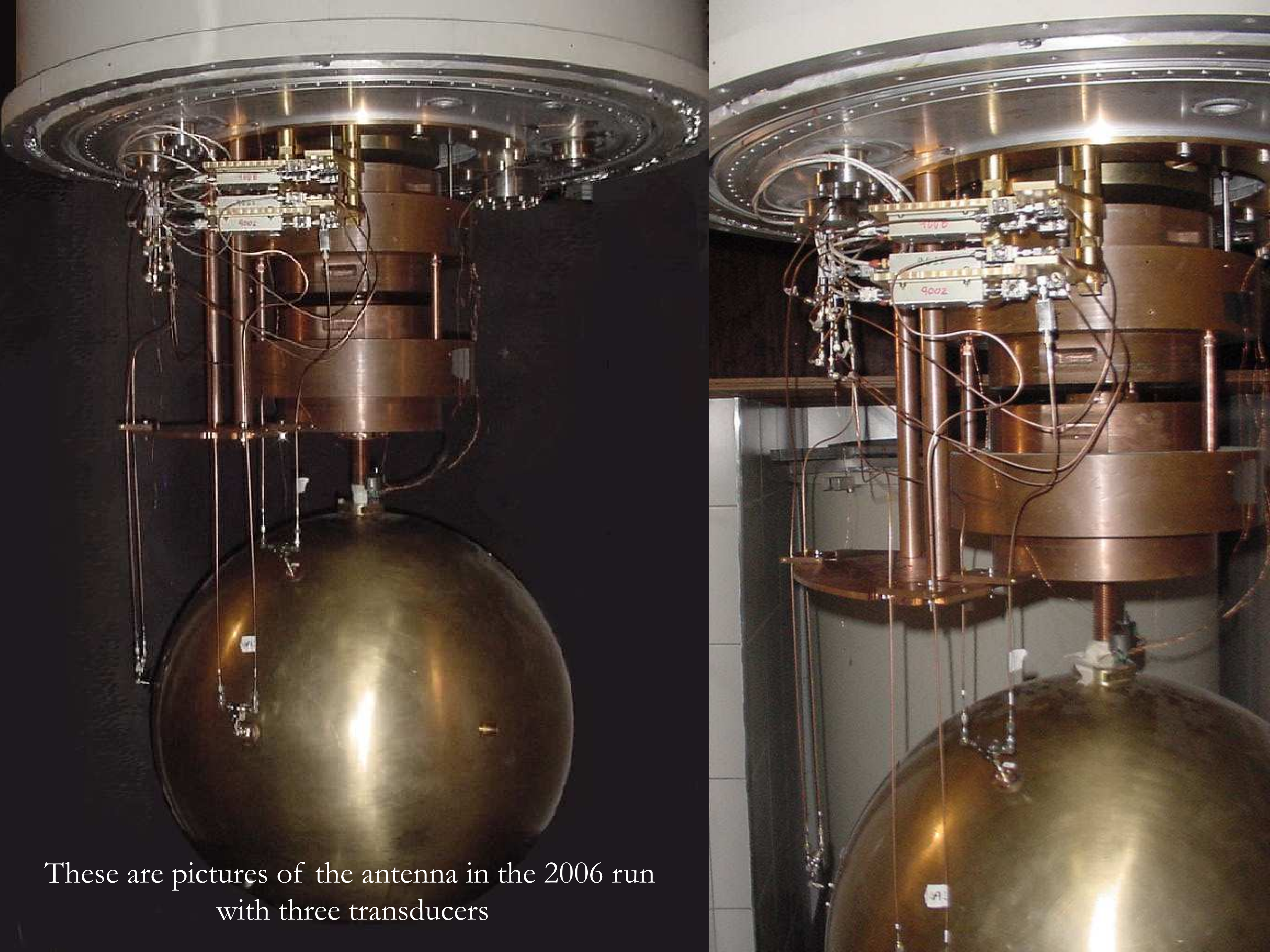
# (Brazil)

**started commissioning operation in the 8th of September, 2006.**

**It involves a collaboration between INPE, USP, ITA, PUC-Rio, IFSP, UNICAMP, CBPF, UNIFESP, UNESP, UFABC, IAE, UNIPAMPA, UESC, Leiden University, UWA, LSU, OCA, and it has been supported by**



GRAVITON GROUP



These are pictures of the antenna in the 2006 run with three transducers


Computer/gps data acquisition system
Mezzanine
The helium return line
This is a picture of the antenna in 2009

Amaldi 9 and NRDA 2011 IOP Publishing
Journal of Physics: Conference Series **363** (2012) 012003 doi:10.1088/1742-6596/363/1/012003

# Status Report of the Schenberg Gravitational Wave Antenna

**O D Aguiar[1], J J Barroso[1], N C Carvalho[1], P J Castro[1], C E Cedeño M[1], C F da Silva Costa[1], J C N de Araujo[1], E F D Evangelista[1], S R Furtado[1], O D Miranda[1], P H R S Moraes[1], E S Pereira[1], P R Silveira[1], C Stellati[1], N F Oliveira Jr[2], Xavier Gratens[2], L A N de Paula[2], S T de Souza[2], R M Marinho Jr[3], F G Oliveira[3], C Frajuca[4], F S Bortoli[4], R Pires[4], D F A Bessada[5], N S Magalhães[5], M E S Alves[6], A C Fauth[7], R P Macedo[7], A Saa[7], D B Tavares[7], C S S Brandão[8], L A Andrade[9], G F Marranghello[10], C B M H Chirenti[11], G Frossati[12], A de Waard[12], M E Tobar[13], C A Costa[14], W W Johnson[14], J A de Freitas Pacheco[15], G L Pimentel[16]**

[1] INPE – Divisão de Astrofísica, São José dos Campos, SP, Brazil,
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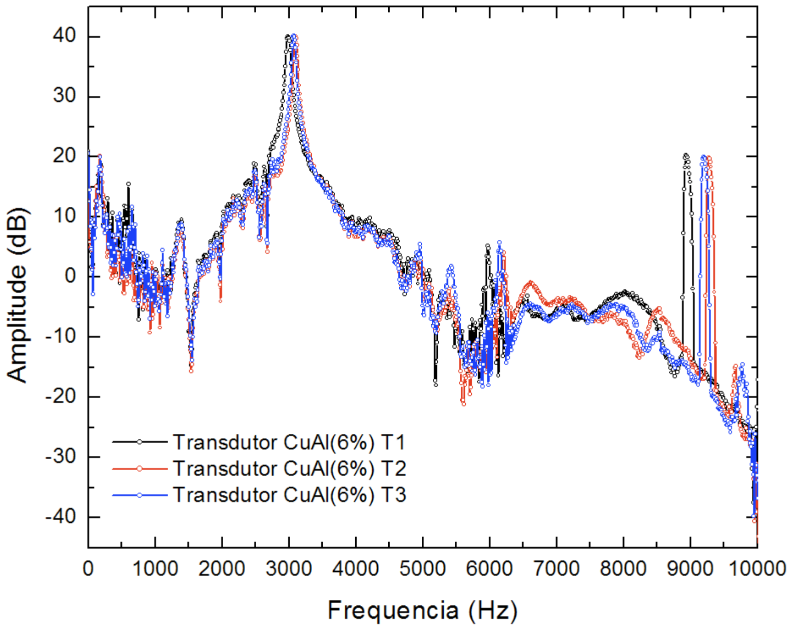
[3] Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brazil,
[4] Instituto Federal de São Paulo, São Paulo, SP, Brazil,
[5] Universidade Federal de São Paulo, Diadema, SP, Brazil,
[6] Universidade Federal de Itajubá, Itajubá, MG, Brazil,
[7] Universidade Estadual de Campinas, Instituto de Física, Campinas, SP, Brazil,
[8] Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil,
[9] Instituto de Aeronáutica e Espaço, São José dos Campos, SP, Brazil,
[10] Universidade Federal de Bagé, Bagé, RS, Brazil,
[11] Universidade Federal do ABC, Santo André, SP, Brazil,
[12] Leiden University, Kammerlingh Onnes Laboratory, Leiden, The Netherlands,
[13] University of Western Australia, Perth, Australia,
[14] Louisiana State University, Baton Rouge, USA,
[15] Observatoire de la Côte dAzur, Nice, France,
[16] Princeton University, Princeton, USA.

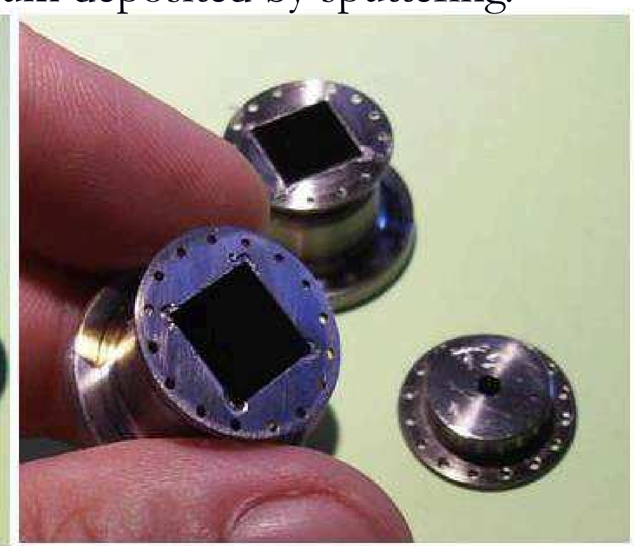
The three initial transducers:

$Q_e \sim 10^3$

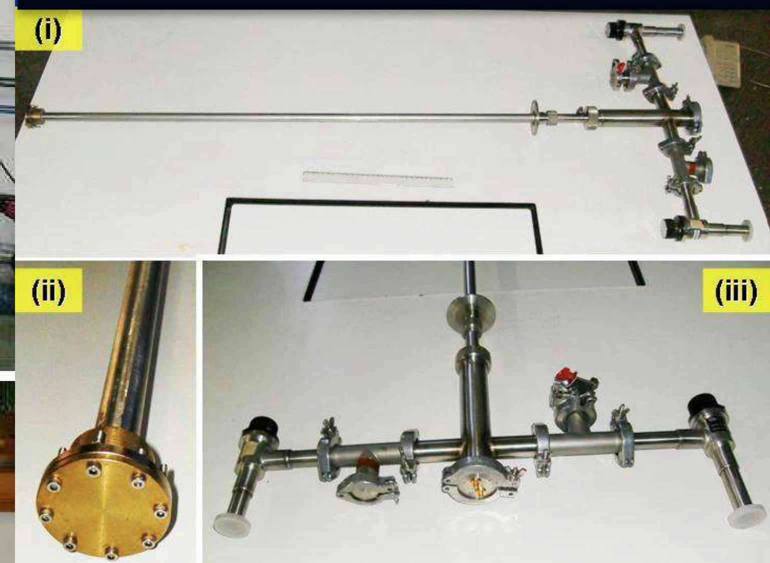
Measurements of the mechanical resonant frequencies of three transducers.



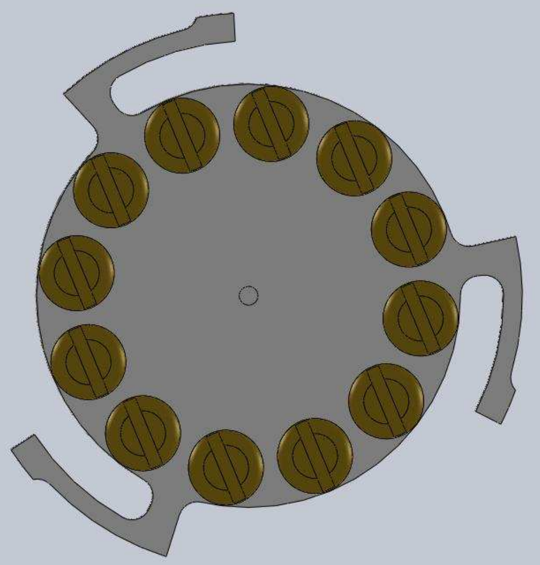

Silicon membranes with niobium deposited by sputtering.



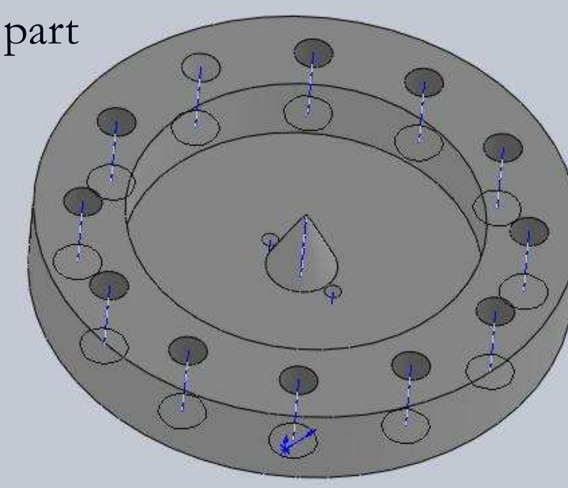

Electrical quality factors (Qe) of several superconducting reentrant cavities at 4.2 K were measured using a liquid helium cooled dewar. Qe as high as 300 k were found.




Experimental apparatus for testing superconducting reentrant cavities within a liquid helium cooled dewar.

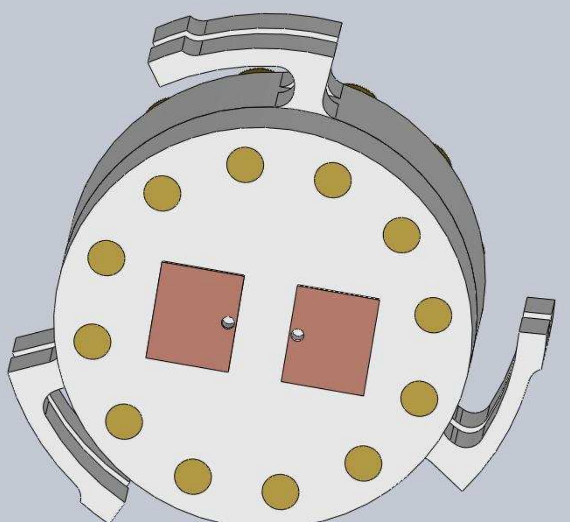


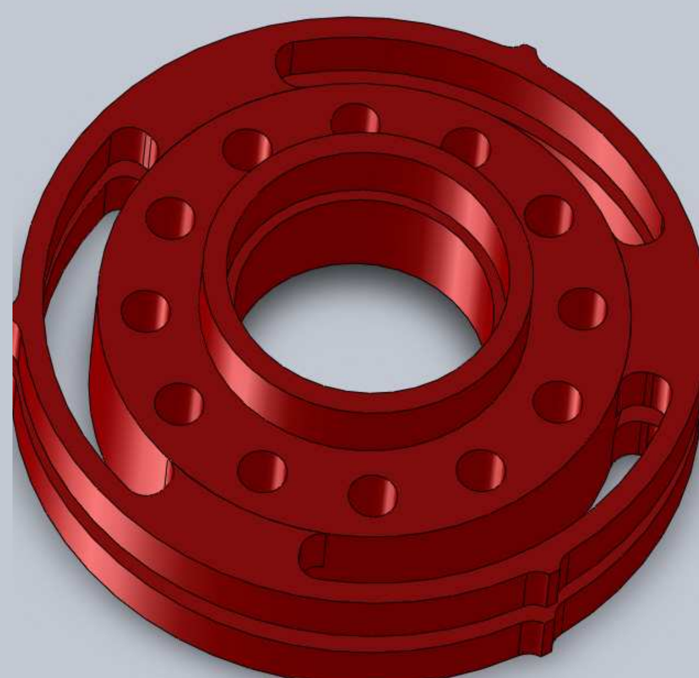
Alumina part



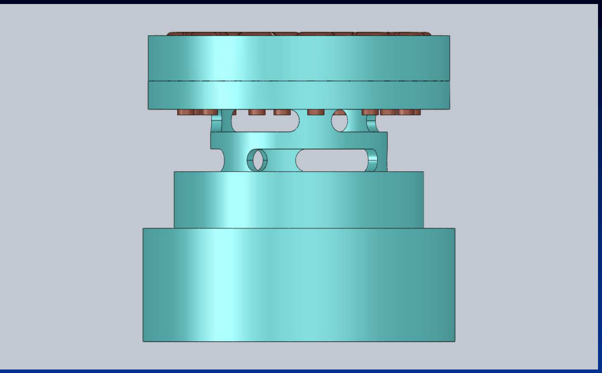
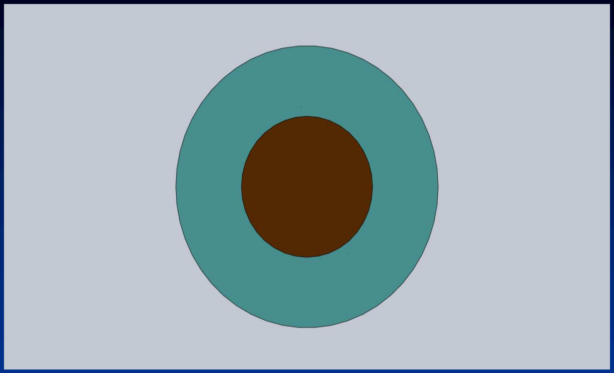
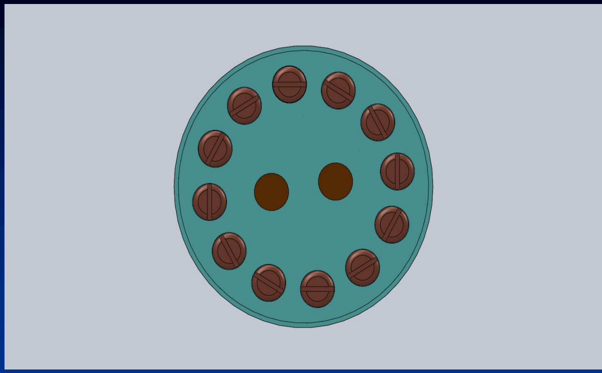
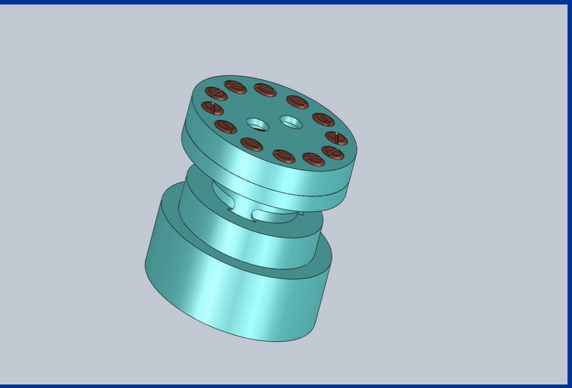
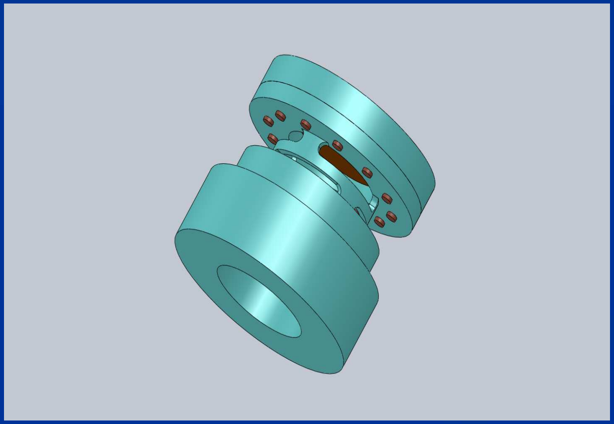
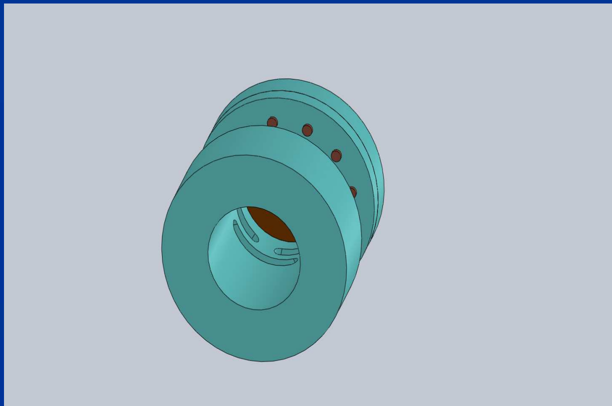
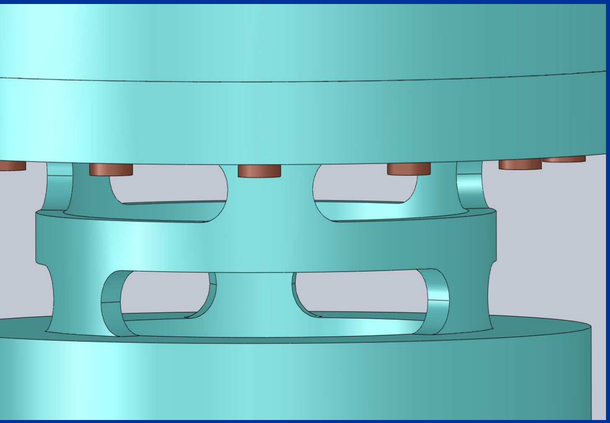
# Fourth design

# Third design

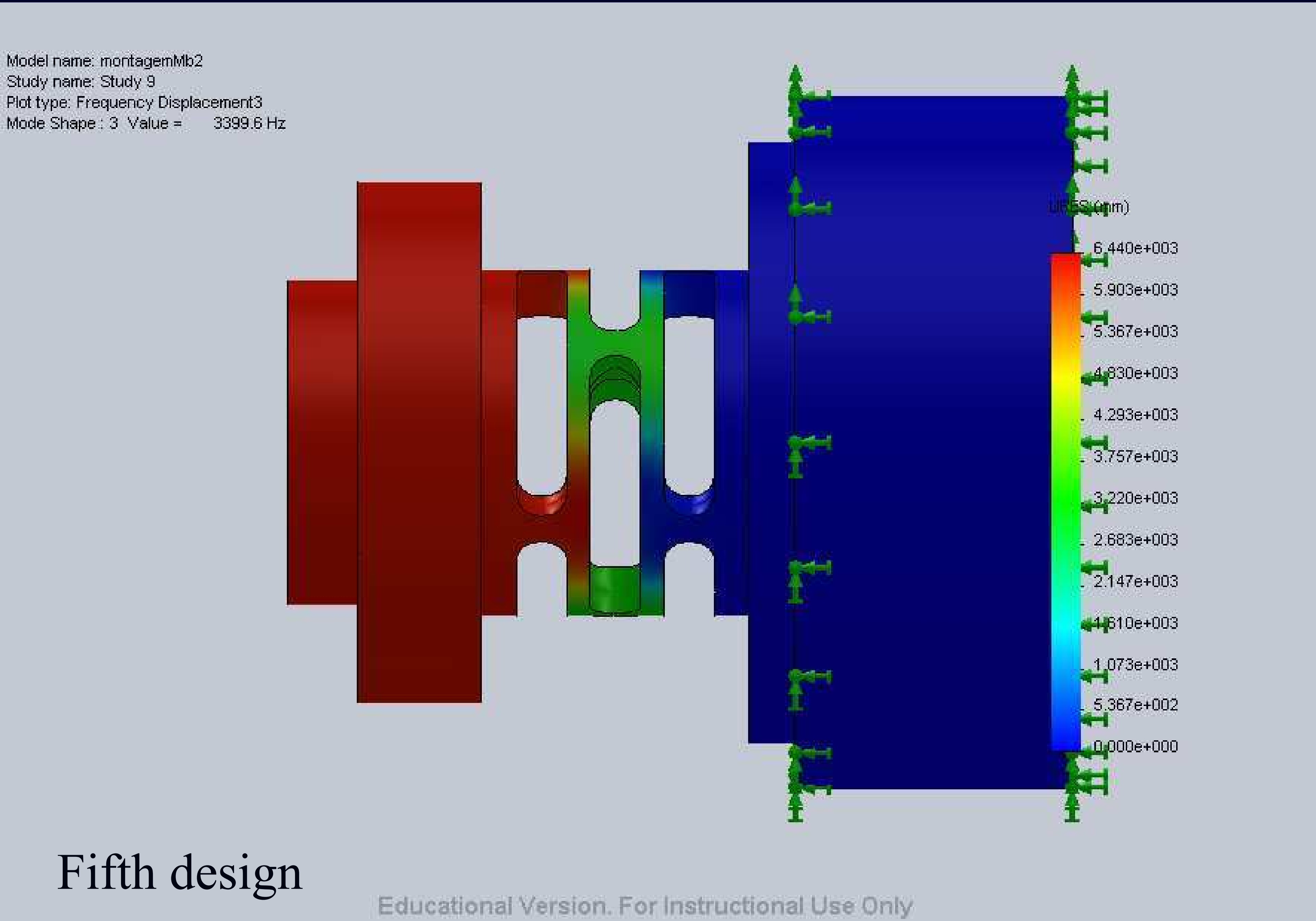




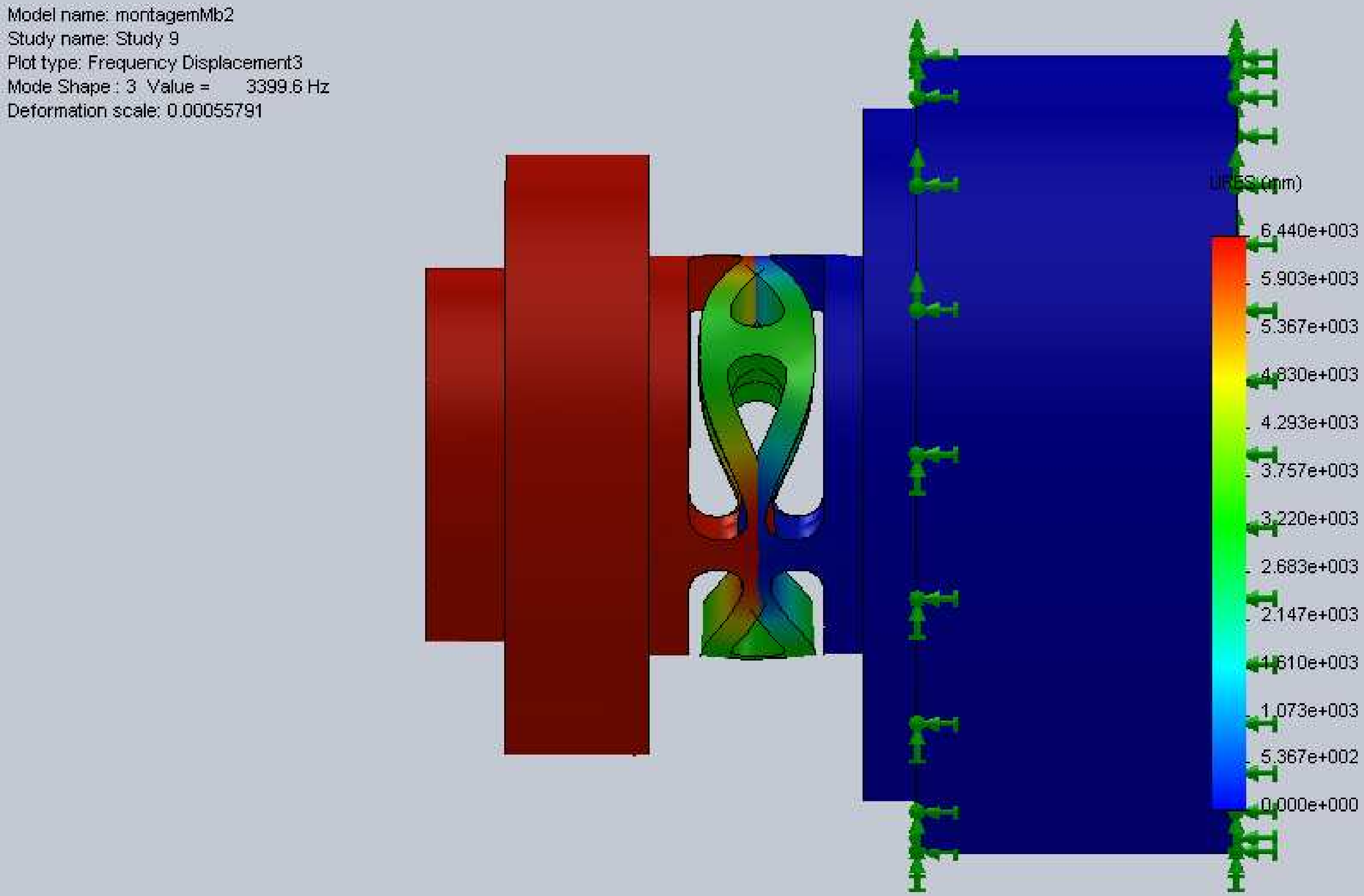
Niobium part

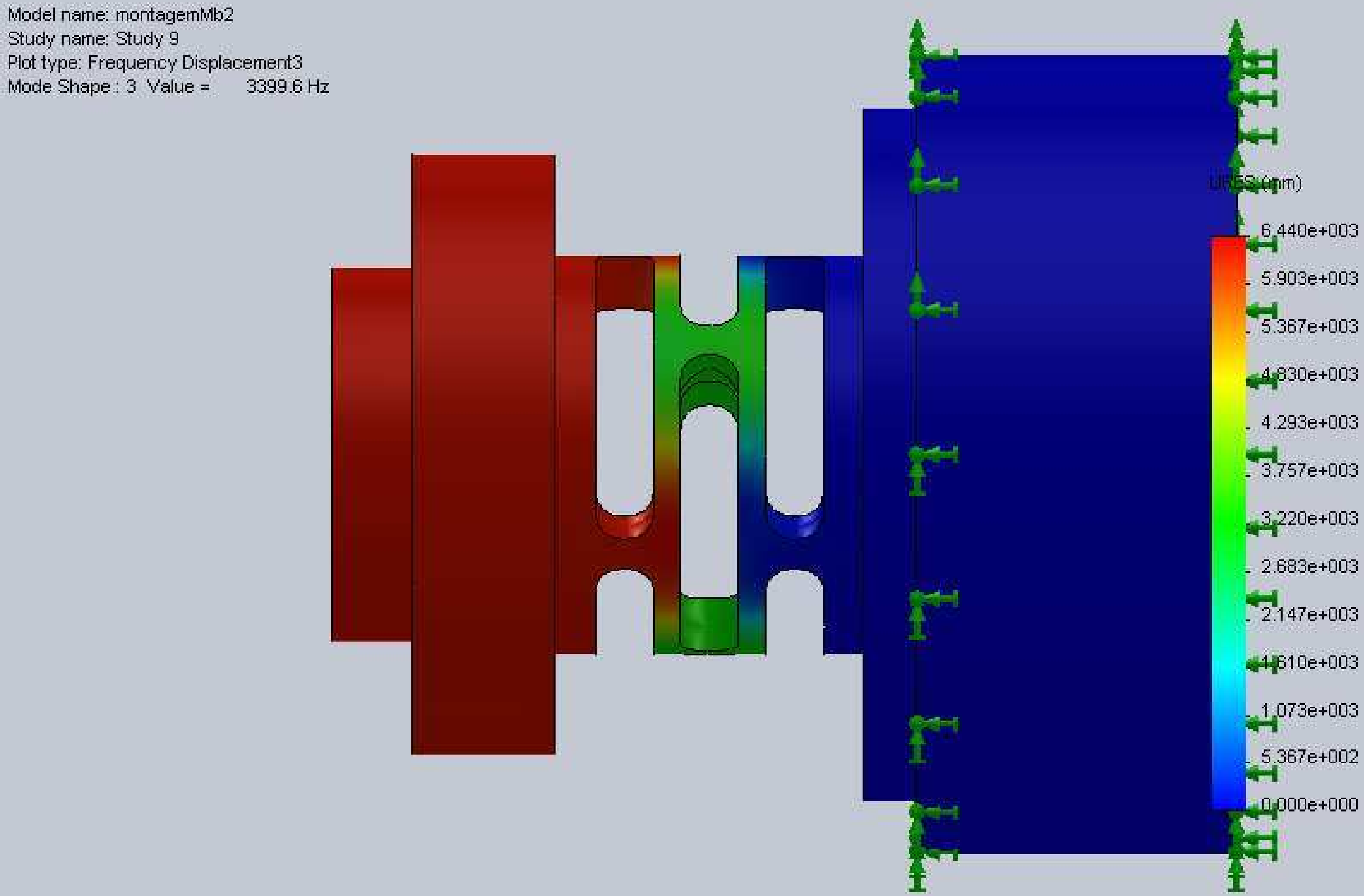
Fifth design




Fifth design



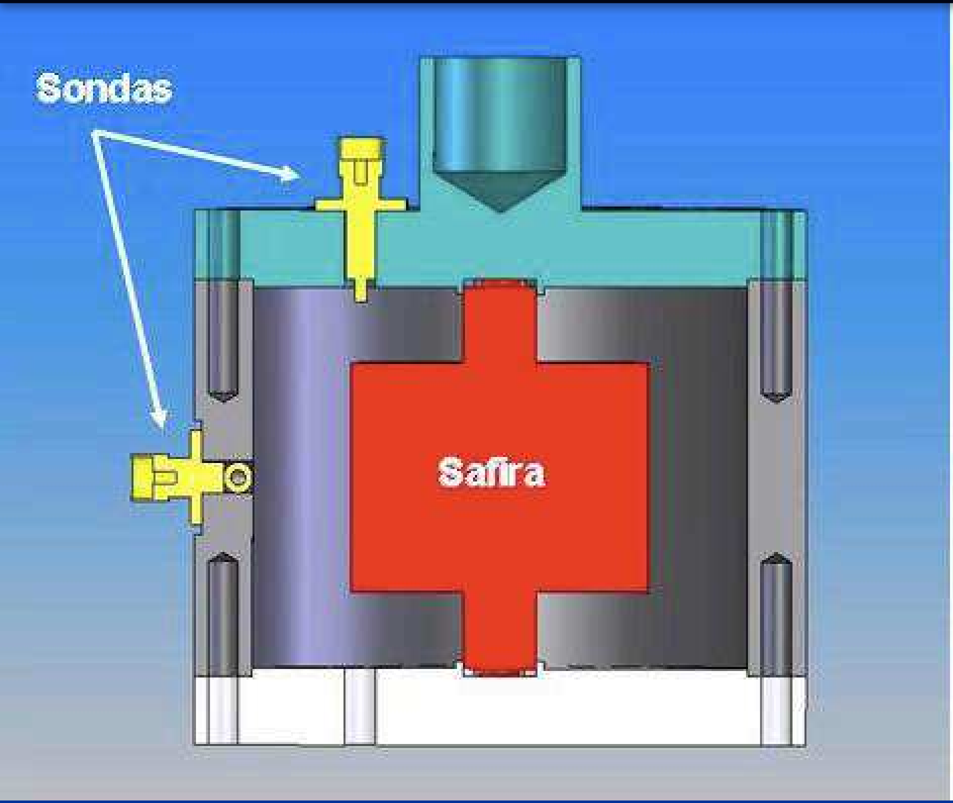

Fifth design

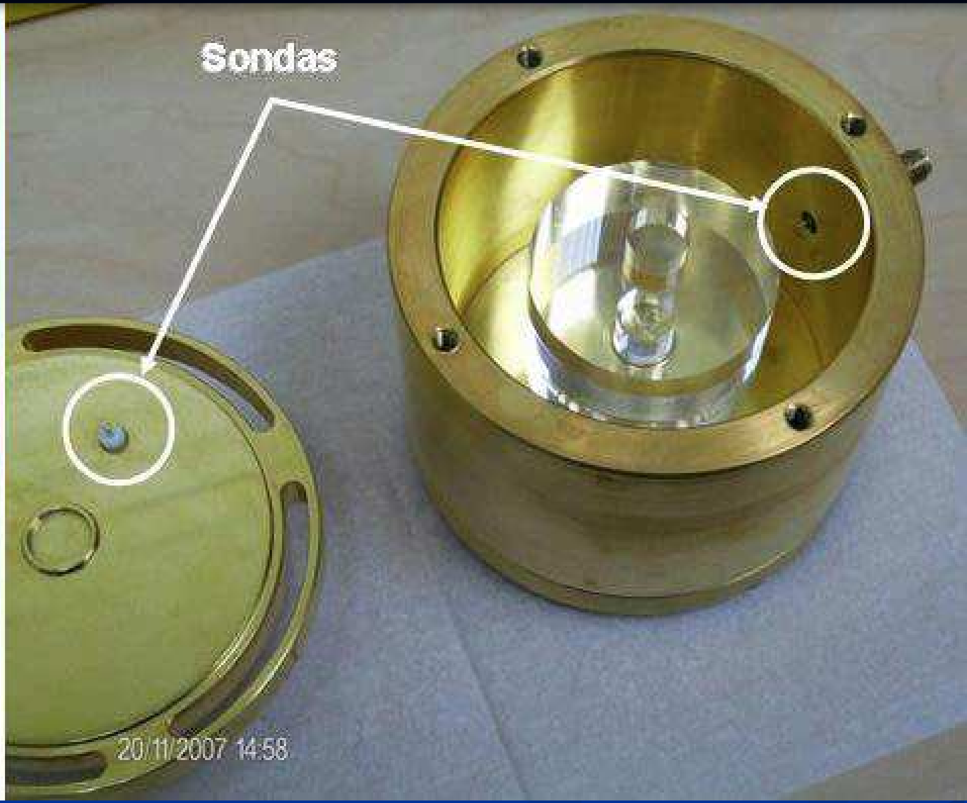



# Fifth design

The eight niobium transducers.

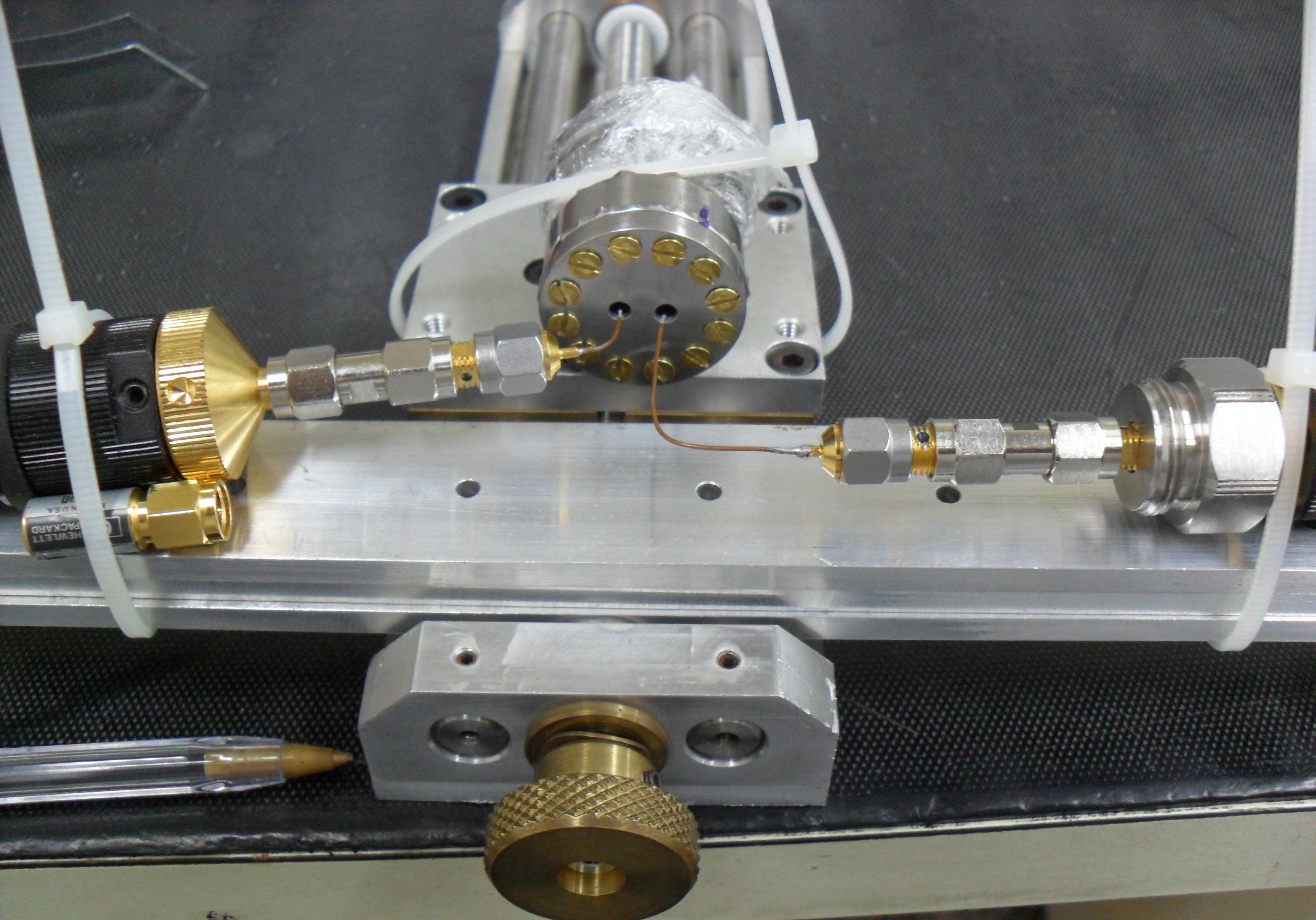
We have developed, in collaboration with the Australian group, very low phase noise sapphire oscillators that operate at 77 K.




THALES
J.Prolab
We do the assembling of transducers in an INPE Clean Room

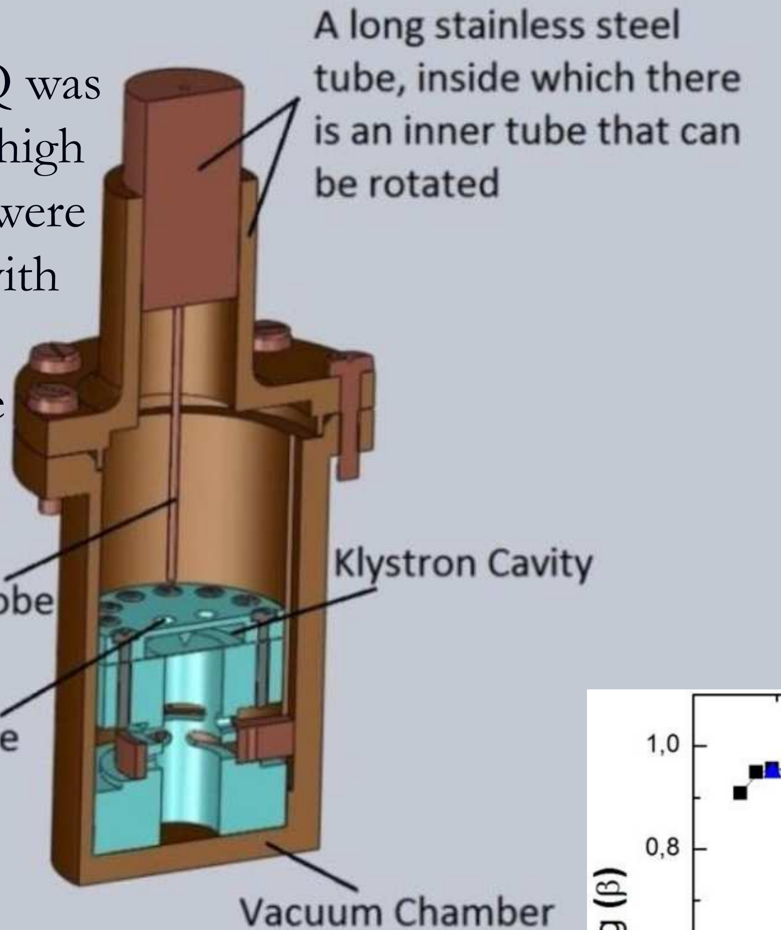
This is a close view of the niobium transducers

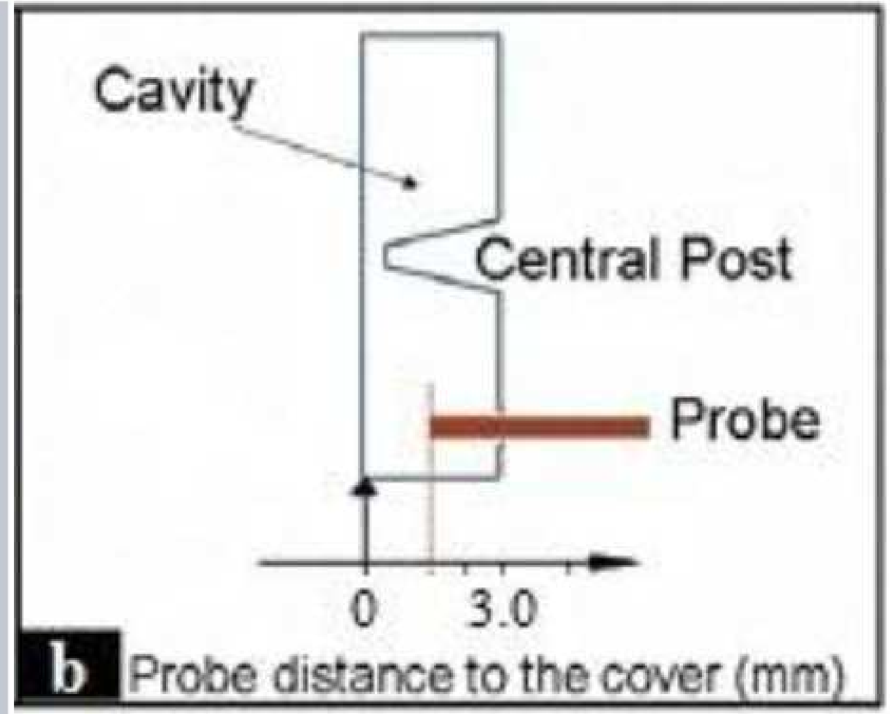


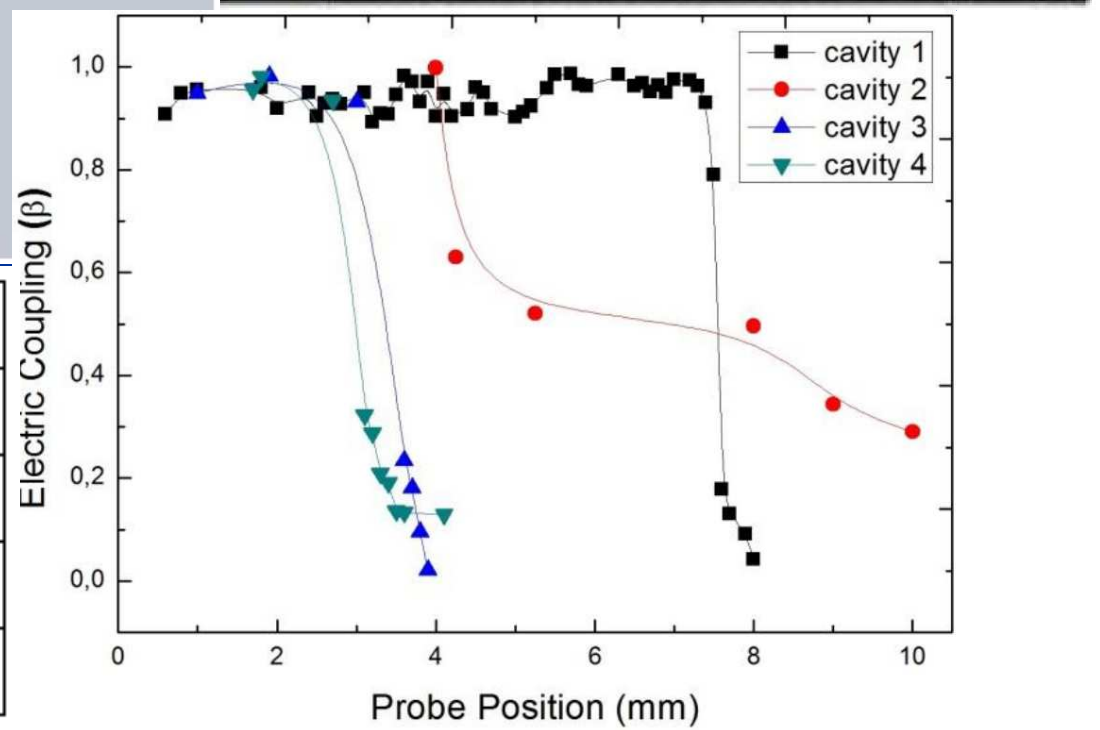

Here we are measuring the microwave resonant frequency of the transducer

And here we are measuring the cavity electrical Q and also the coupling of a probe positioned outside the cavity, which was dipped in LHe (4.2 K)

When the electrical Q was very high, high couplings were achieved with the probe outside the cavity




| Cavity | $D$ (mm) | $P$ (mm) | $\beta$ |
|---|---|---|---|
| 3 | 1.5 | 3.9 | 0.02 |
| 4 | 2.5 | 4.1 | 0.13 |
| 1 | 3.0 | 8.0 | 0.04 |
| 2 | 3.5 | 10.0 | 0.29 |

JINST
PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

We presented
these results in
this publication.

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PUBLISHED: *March 3, 2015*

# High sensitivity niobium parametric transducer for the Mario Schenberg gravitational wave detector

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*Praça Marechal-do-Ar Eduardo Gomes 50, São José dos Campos, Brazil*
[b] *Department of Mechanics and Material Physics, University of Sao Paulo – USP,*
*Rua do Matão 187, São Paulo, Brazil*
[c] *Astrophysics Division, National Institute for Space Research – INPE,*
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*35 Stirling Hwy, 6009 Crawley, Western Australia, Australia*

*E-mail:* leandroifusp@yahoo.com

We measured the two mechanical resonant frequencies of the transducer and also did electromagnetic simulations of the transducer microwave cavity with a special software (CST Studio Suite)

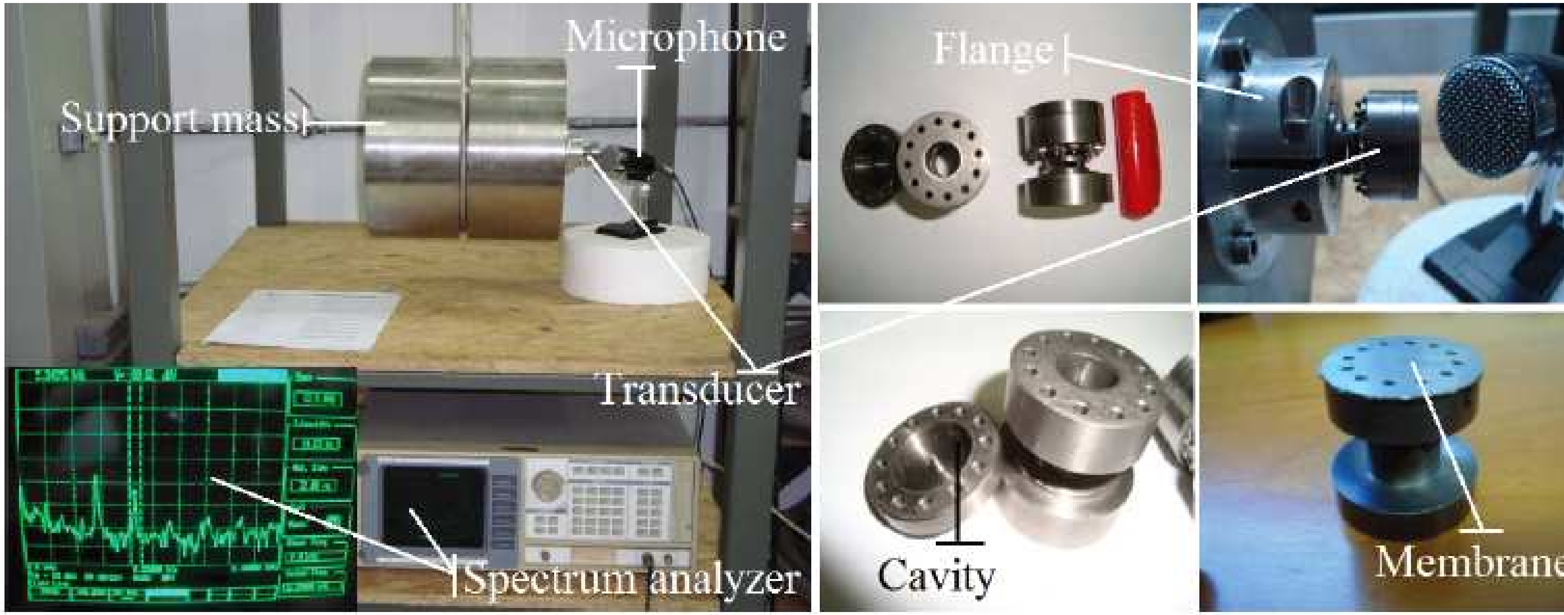



**Figure 2.** Equipment for measurements of mechanical resonance frequencies. The transducers were attached to the support mass and the normal modes were excited by striking the transducer. The vibrations were shown on a spectrum analyzer.

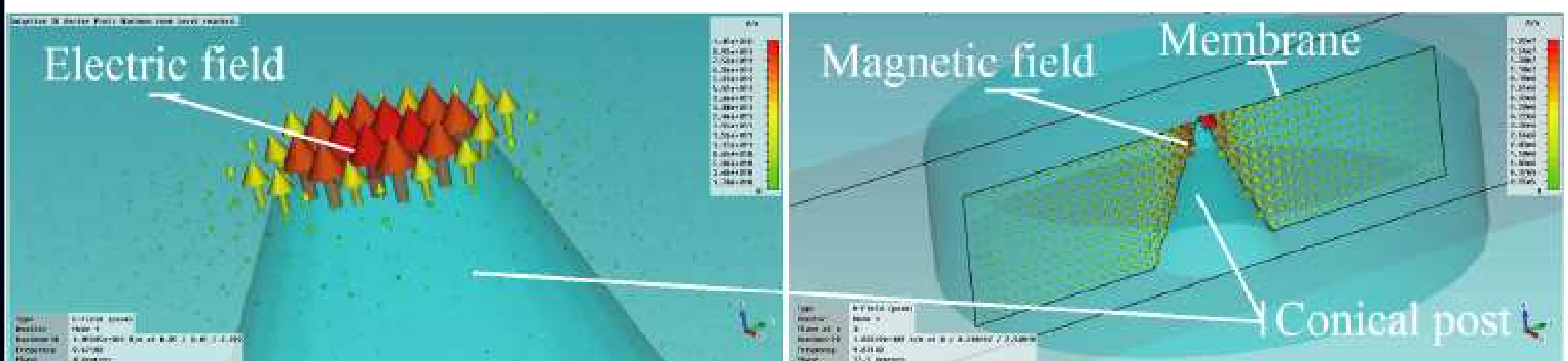


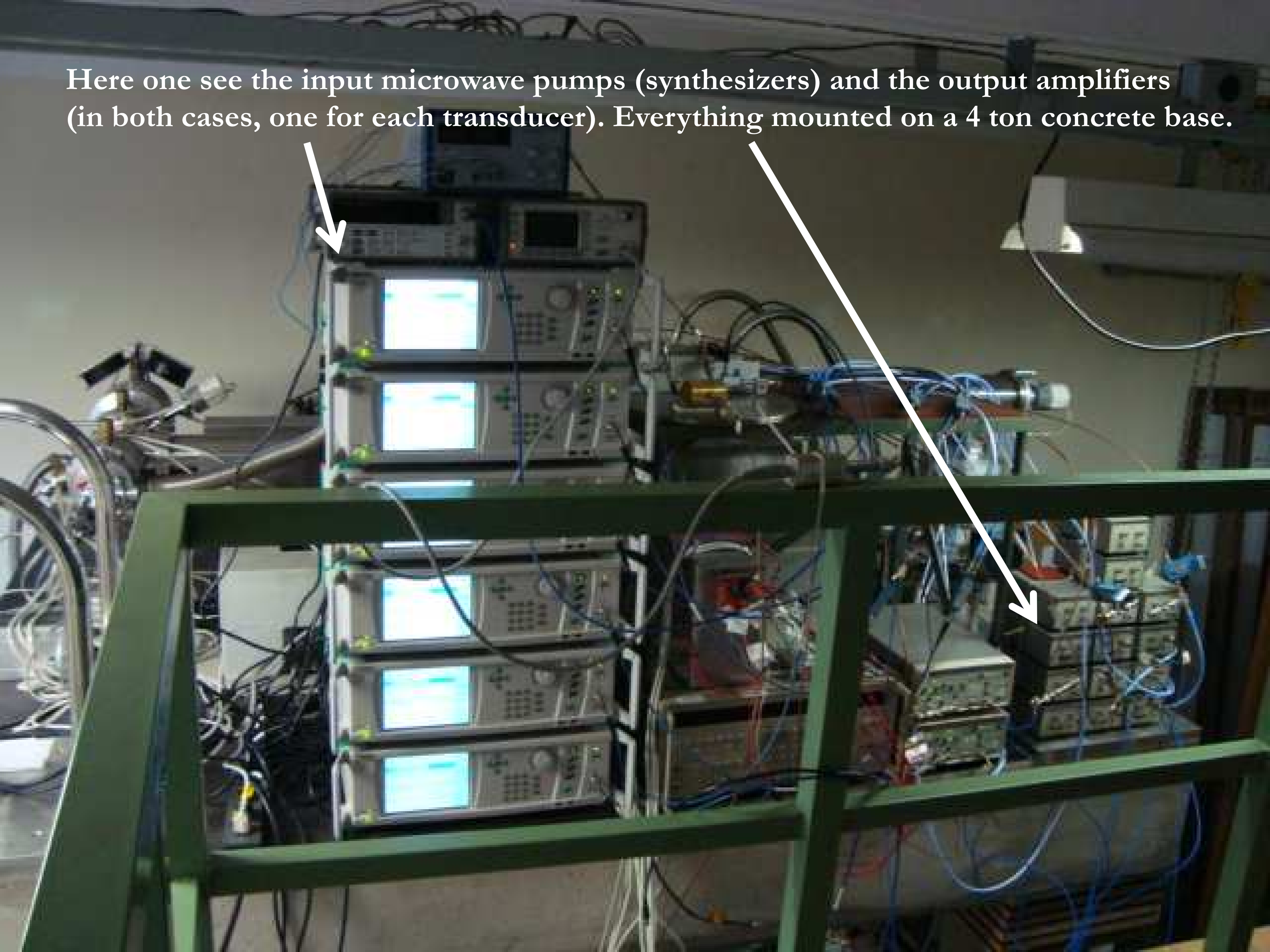

**Figure 3.** Electric and magnetic fields of the klystron mode for the gap of $\sim 3\,\mu$m. The electric field is much stronger at the gap region, i.e. between the top of the post and the membrane. The magnetic field shows a cylindrical symmetry around the conical post.

We adjusted the electrical resonant frequencies of all microwave cavities

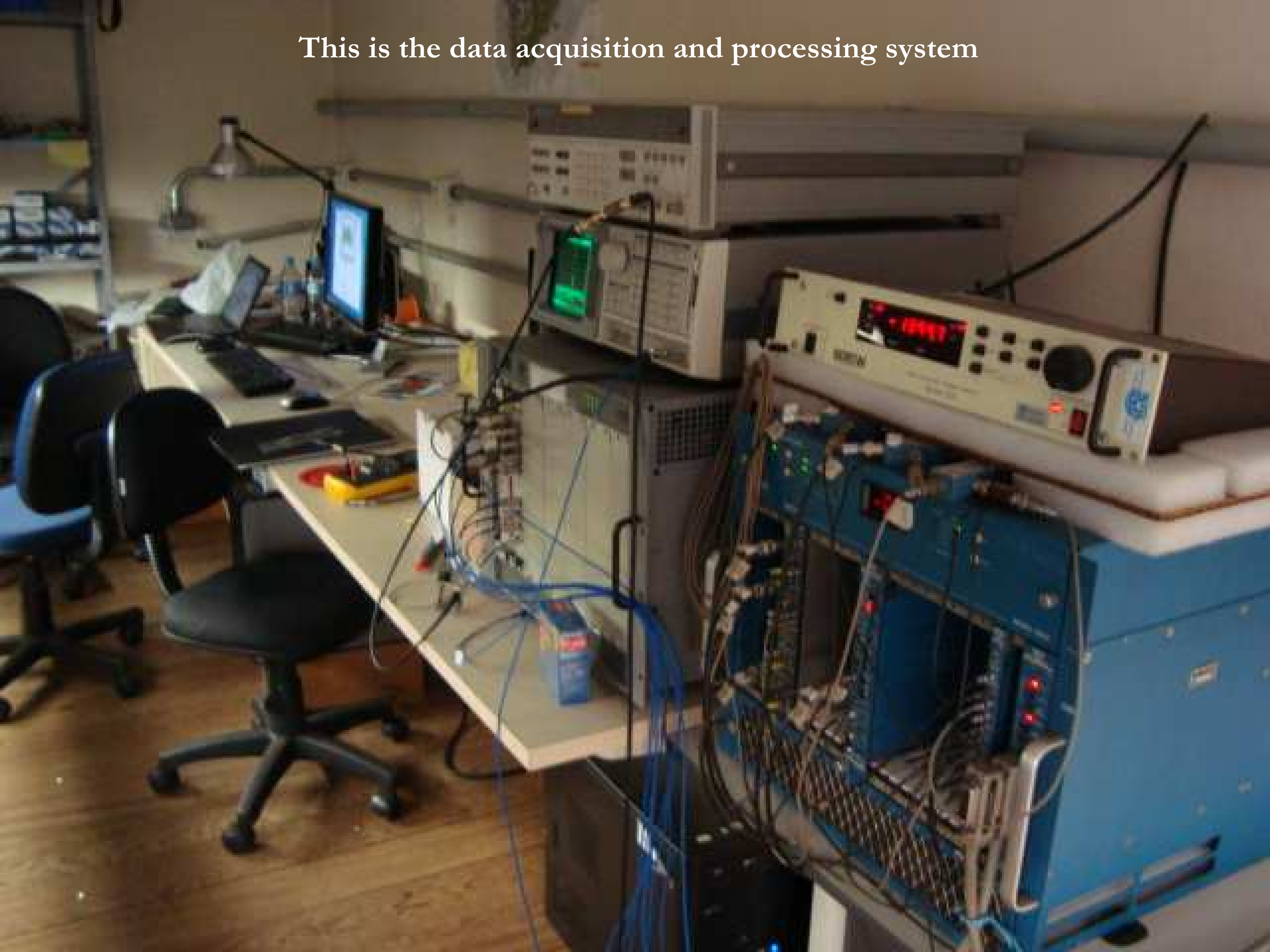
**Table 2.** Frequencies of eight samples that were submitted to eight successive steps of adjustment each one.

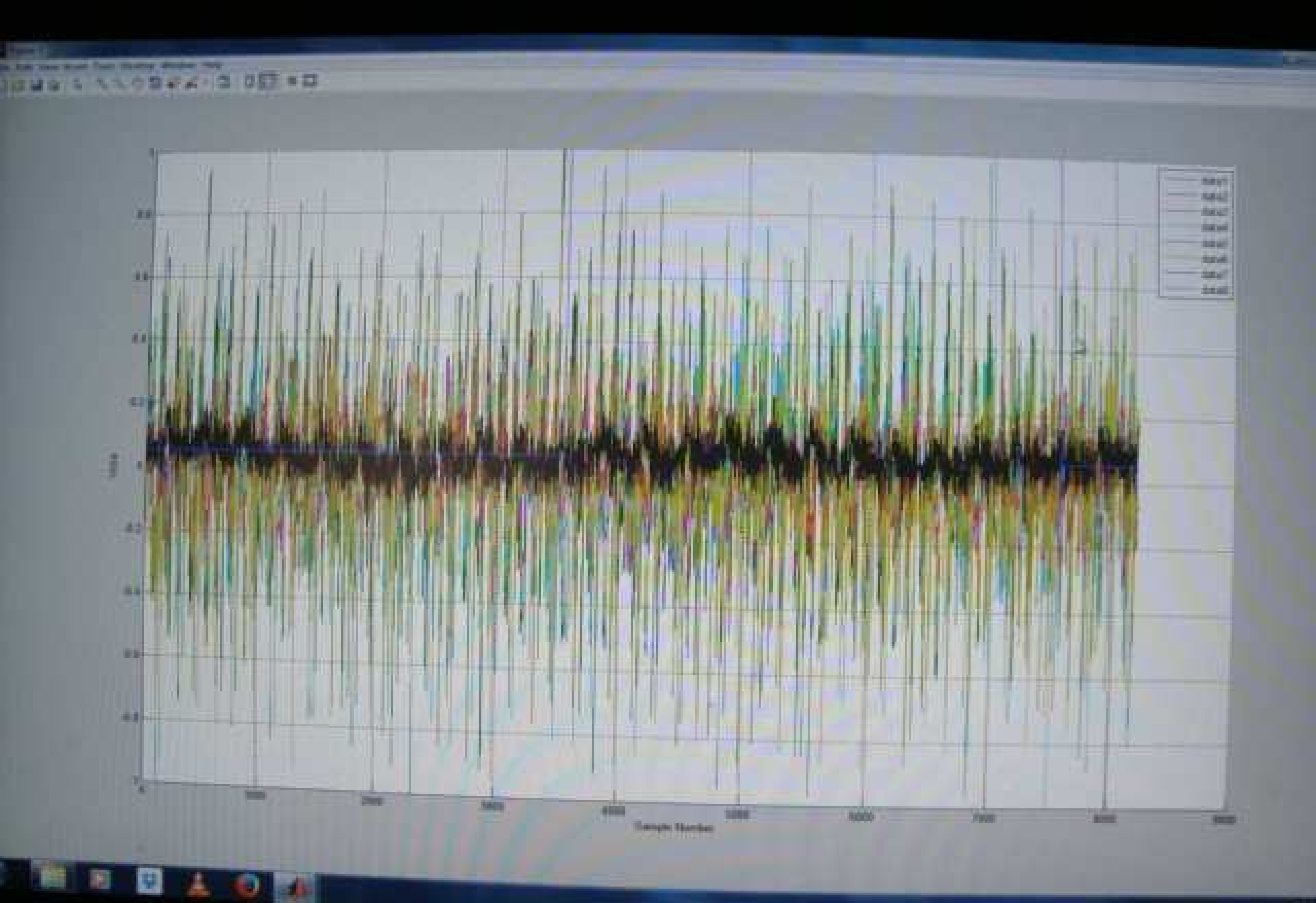
| Sample | Cavity Frequencies [GHz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | step 1 | step 2 | step 3 | step 4 | step 5 | step 6 | step 7 | step 8 |
| 1 | 12.76 | 12.88 | **9.52** | **9.52** | **9.52** | **9.52** | **9.52** | **9.52** |
| 2 | 12.44 | 12.32 | **9.52** | **9.52** | **9.52** | **9.52** | **9.52** | **9.52** |
| 3 | 13.40 | 13.88 | 13.36 | 13.16 | 12.76 | 12.32 | 12.06 | 11.08 |
| 4 | 10.96 | 10.92 | **9.88** | **9.88** | **9.88** | **9.88** | **9.88** | **9.88** |
| 5 | 13.12 | 13.28 | 13.00 | 12.76 | 12.64 | 11.92 | 11.56 | 10.54 |
| 6 | 12.64 | 13.20 | 12.36 | 12.00 | 11.74 | 12.52 | 12.20 | 12.13 |
| 7 | **9.76** | **9.76** | **9.76** | **9.76** | **9.76** | **9.76** | **9.76** | **9.76** |
| 8 | 11.28 | 11.28 | 10.60 | 10.08 | **9.48** | **9.48** | **9.48** | **9.48** |


**Figure 4.** Frequency measurements in the vector network analyzer. The measurements were accomplished by transmission by inserting two probes into the cavity. A table for micrometric adjustment was also used in order to improve the accuracy in the probe position.


Here one see the input microwave pumps (synthesizers) and the output amplifiers
(in both cases, one for each transducer). Everything mounted on a 4 ton concrete base.

# This is the data acquisition and processing system





**Here one see the output signal of the seven transducers in the 2015 Oct/Nov run**


This a picture of the antenna at the São Paulo (USP) site during the 2015 runs
$h \sim 10^{-19} - 10^{-20}\ Hz^{-1/2}$

Sphere radius = 0.325 m; df/dx = $7.26 \times 10^{14}$ Hz/m*
Amplitude conversion factor (membrane to sphere surface) → 1/4815

**T1 ~ T2 ~ T3:** 1 $mV_{rms}$/100 kHz = $10^{-8}$ $V_{rms}$/Hz
→ $6.9 \times 10^{-16}$ m/$Hz^{1/2}$ --> $h_{1,2,3} = 4.4 \times 10^{-19}/Hz^{1/2}$

**T4:** 3.5 $mV_{rms}$/100 kHz = 3.5 x 10^{-8} $V_{rms}$/Hz
→ $6.2 \times 10^{-16}$ m/$Hz^{1/2}$ → $h_4 = 4.0 \times 10^{-19}/Hz^{1/2}$

**T5:** 10 $mV_{rms}$/100 kHz = 10^{-7} $V_{rms}$/Hz
→ $2.2 \times 10^{-16}$ m/$Hz^{1/2}$ → $h_5 = 1.4 \times 10^{-19}/Hz^{1/2}$

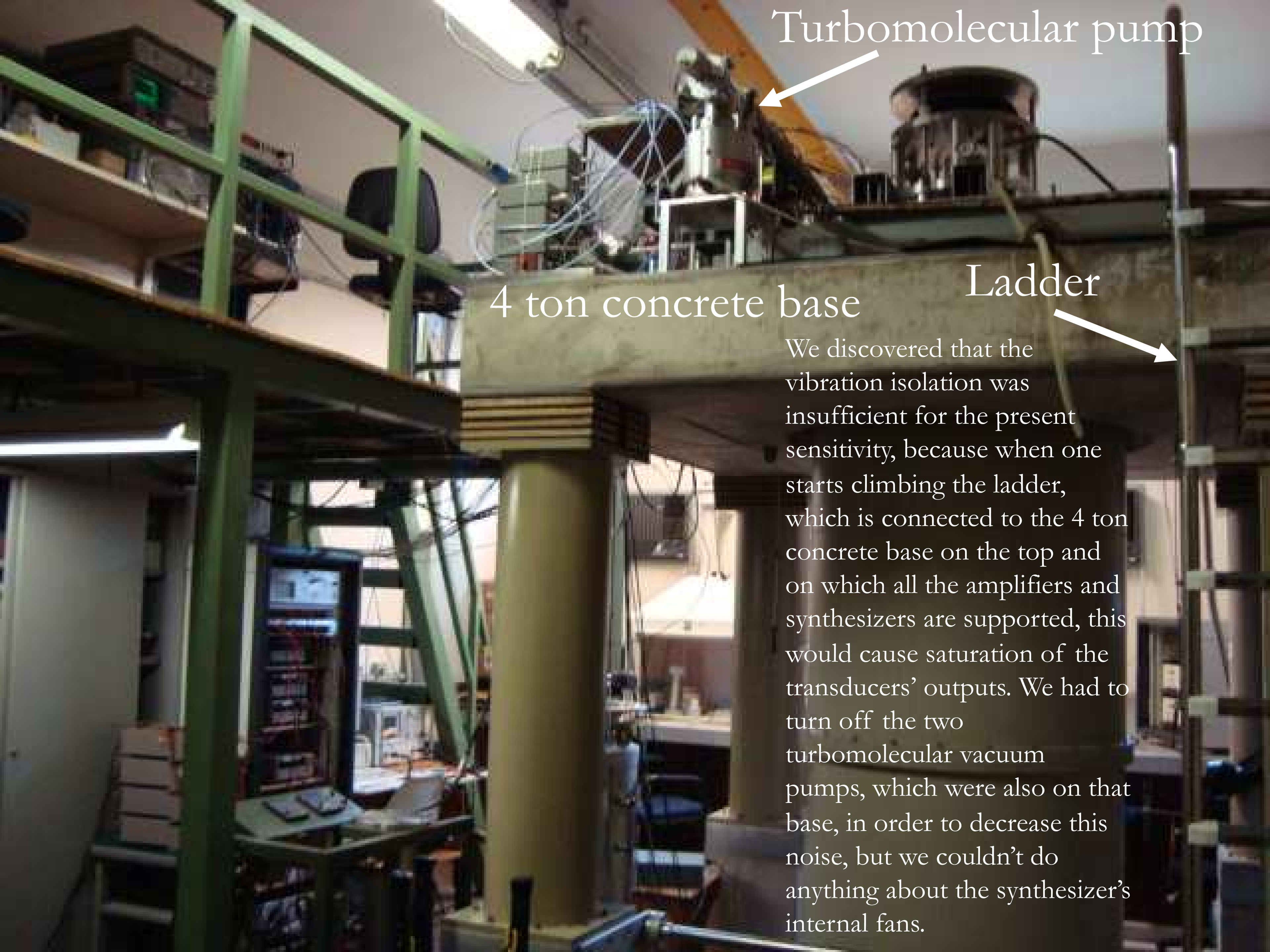
**T6:** 4.5 $mV_{rms}$/100 kHz = 4.5 x 10^{-8} $V_{rms}$/Hz
→ $5 \times 10^{-16}$ m/$Hz^{1/2}$ → $h_6 = 3 \times 10^{-19}/Hz^{1/2}$

**T9:** 50 $mV_{rms}$/100 kHz = 5 x 10^{-7} $V_{rms}$/Hz
→ $8.8 \times 10^{-17}$ m/$Hz^{1/2}$ → $h_9 = 5.6 \times 10^{-20}/Hz^{1/2}$

**T9' (under special conditions):** 38 $mV_{rms}$/100 kHz = 3.8 x 10^{-7} $V_{rms}$/Hz
→ $1.8 \times 10^{-17}$ m/$Hz^{1/2}$ → $h_9 = 1.2 \times 10^{-20}/Hz^{1/2}$

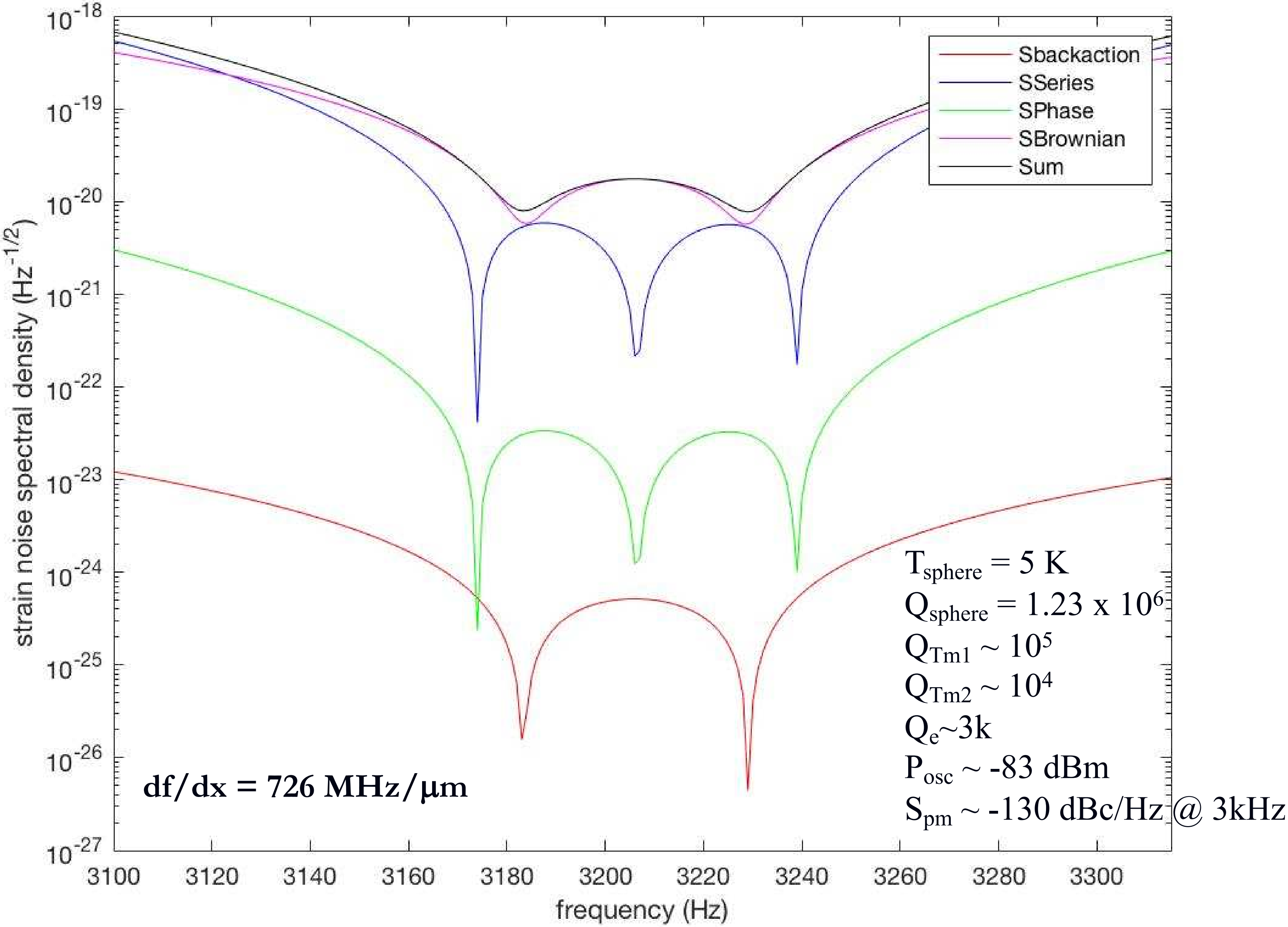
* CARVALHO, N C ; BOURHILL, J ; TOBAR, M E ; AGUIAR, O D . Sensitivity characterization of a parametric transducer for gravitational wave detection through optical spring effect. *Classical and quantum gravity*, v. 34, p. 175001, 2017.

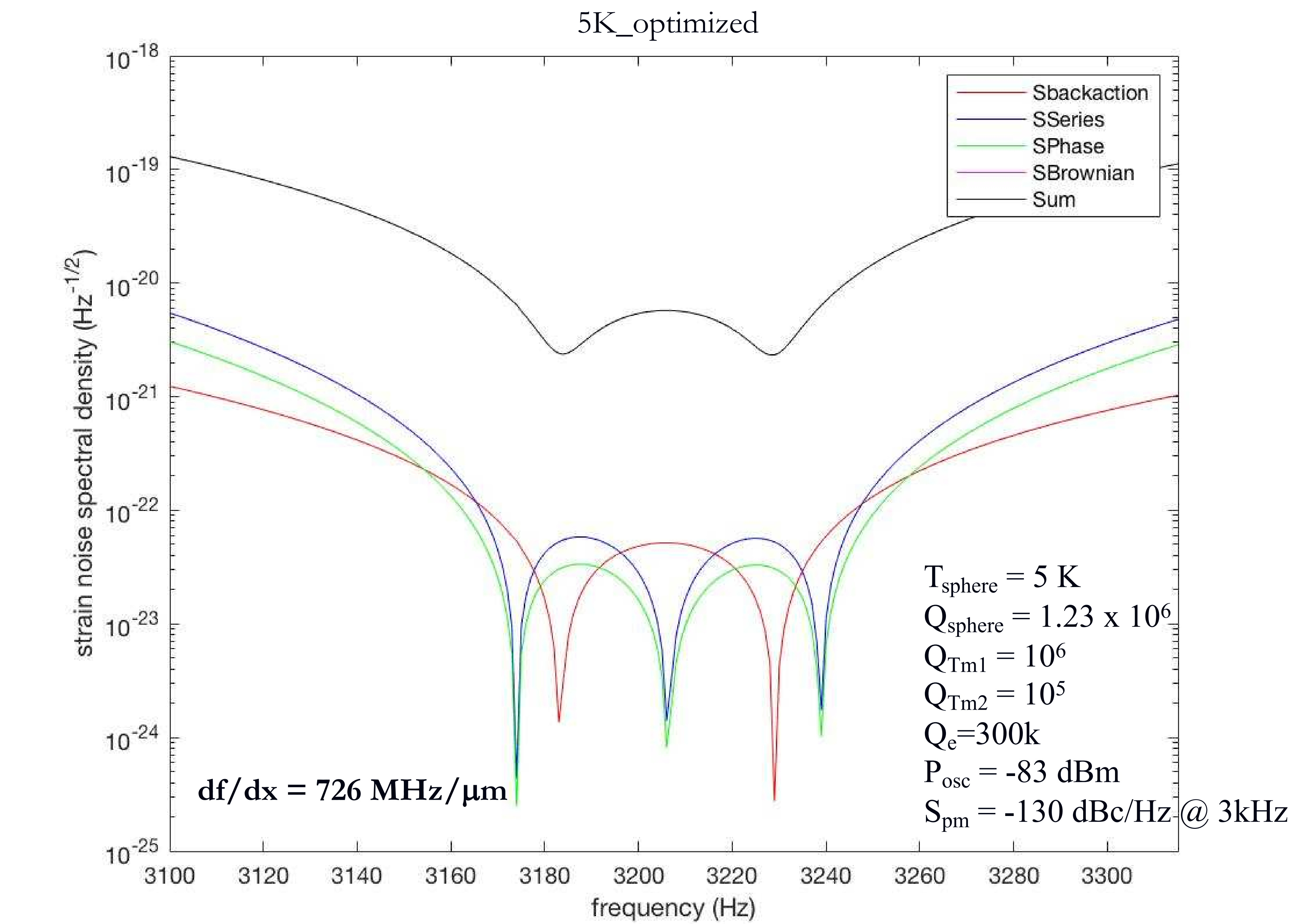
Overall detector sensitivity:
$h^{-2} = \& \, h_i^{-2}$
$h_{quadrupolar}$ (~3.2kHz) = $1.1 \times 10^{-19}/Hz^{1/2}$
$h_{monopolar}$ (~6.5kHz) = $1.2 \times 10^{-20}/Hz^{1/2}$




We discovered that the vibration isolation was insufficient for the present sensitivity, because when one starts climbing the ladder, which is connected to the 4 ton concrete base on the top and on which all the amplifiers and synthesizers are supported, this would cause saturation of the transducers' outputs. We had to turn off the two turbomolecular vacuum pumps, which were also on that base, in order to decrease this noise, but we couldn't do anything about the synthesizer's internal fans.

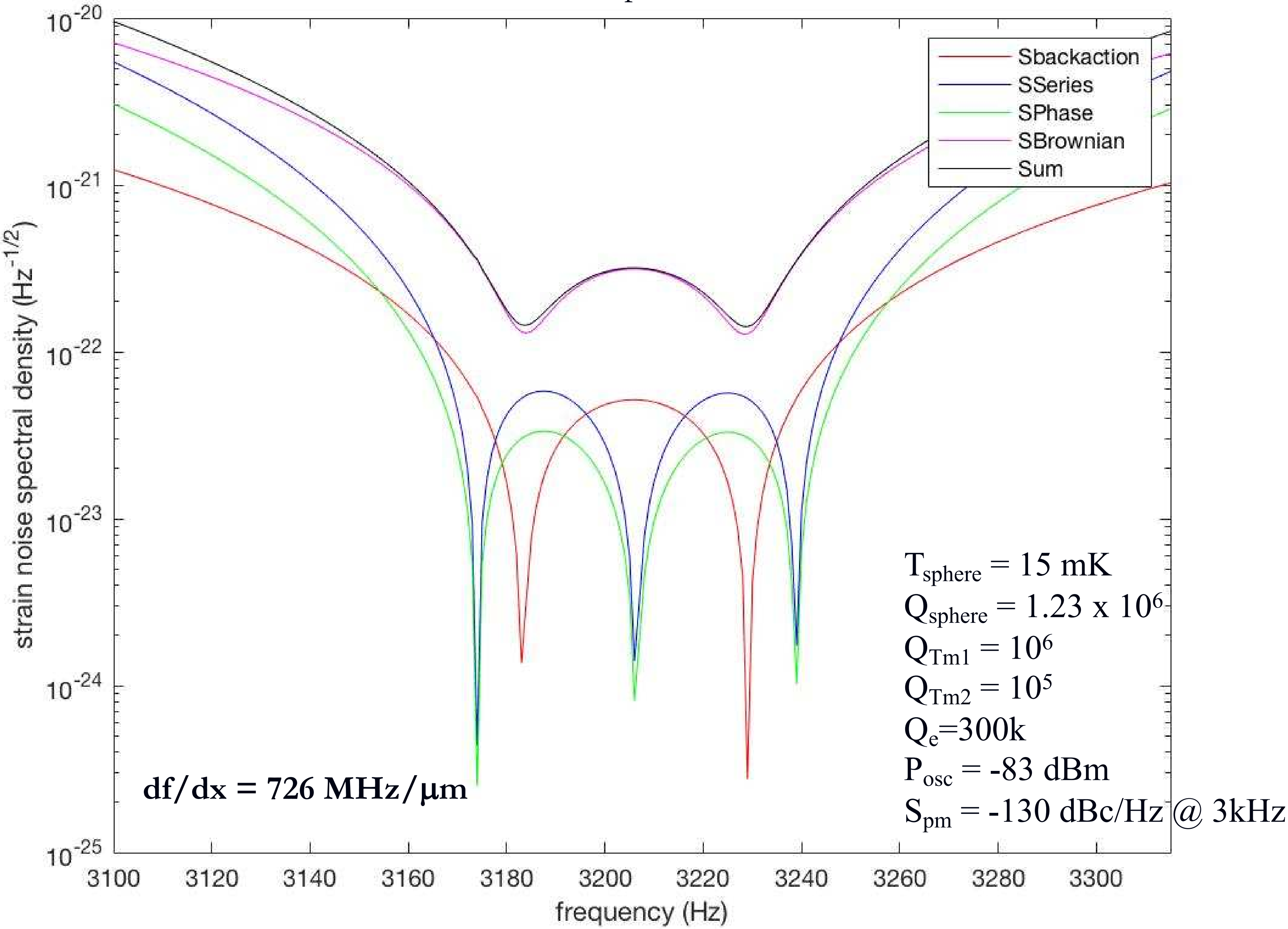
Sensibility for typical parameters used in the 2015 run (seismic noise is not considered)

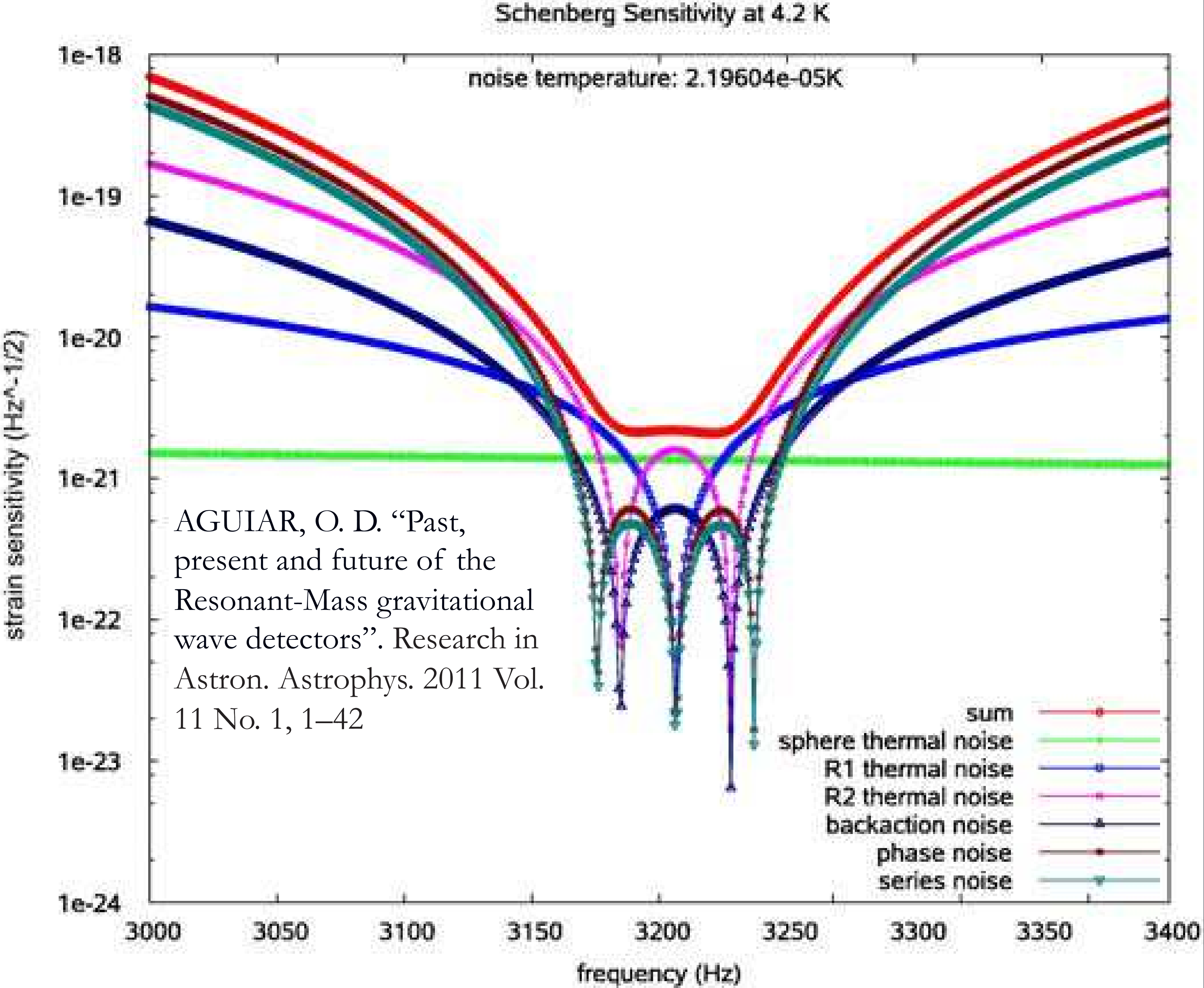




5K_optimized
Sbackaction
SSeries
SPhase
SBrownian
Sum
strain noise spectral density (Hz^-1/2)
frequency (Hz)
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
3100
3120
3140
3160
3180
3200
3220
3240
3260
3280
3300
df/dx = 726 MHz/μm
$T_{sphere}$ = 5 K
$Q_{sphere}$ = 1.23 x $10^6$
$Q_{Tm1}$ = $10^6$
$Q_{Tm2}$ = $10^5$
$Q_e$=300k
$P_{osc}$ = -83 dBm
$S_{pm}$ = -130 dBc/Hz @ 3kHz

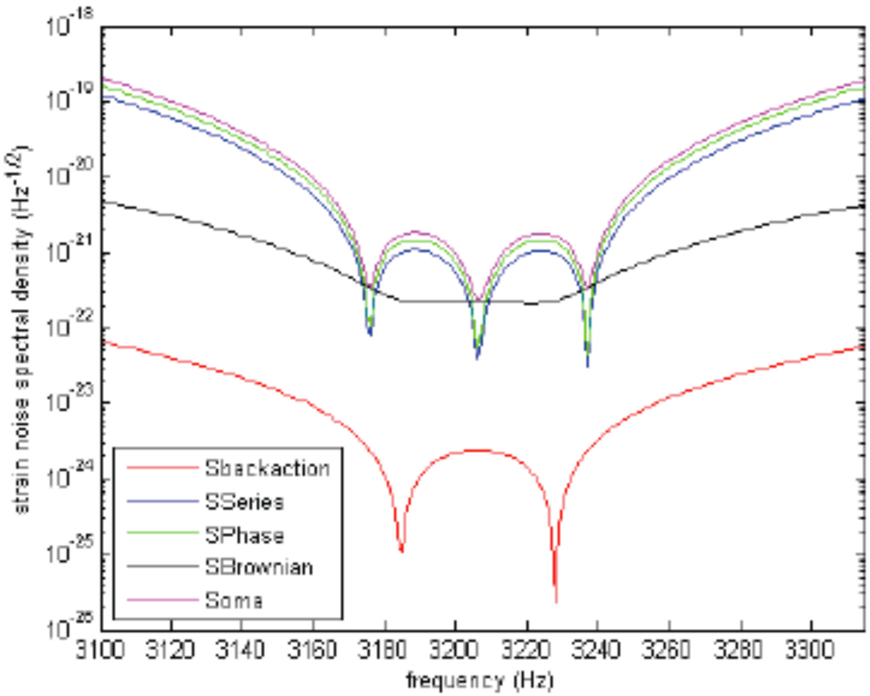
15mK_optimized



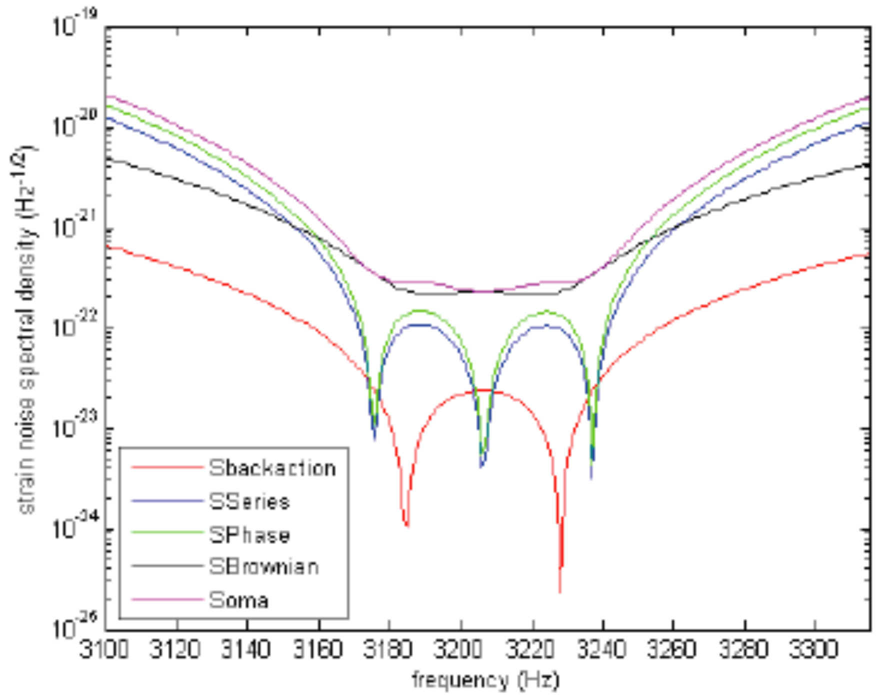



AGUIAR, O. D. “Past, present and future of the Resonant-Mass gravitational wave detectors”. Research in Astron. Astrophys. 2011 Vol. 11 No. 1, 1–42

DE PAULA, L.A.N. ; FERREIRA, E.C. ; CARVALHO, N.C. ; AGUIAR, O.D. . High sensitivity niobium parametric transducer for the Mario Schenberg gravitational wave detector. Journal of Instrumentation, v. 10, p. P03001-P03001, 2015.




a) Strain noise spectral density of the Schenberg detector for the case with the gap of 30 microns (80 MHz/micron)




b) Strain noise spectral density of the Schenberg detector for the case with the gap of 3 microns (800 MHz/micron)

**Figure 5.** Strain noise spectral density of the Schenberg detector for a gap of 30 $\mu$m (80 MHz/$\mu$m) and 3 $\mu$m (800 MHz/$\mu$m). For both cases, we used the thermodynamic temperature of 50 mK, Q $\sim 1 \times 106$, $P_{in} \sim 1 \times 10^{-10}$ Watts, phase noise of $-130$ dBc/Hz@3,2 kHz.

B. P. Abbott et al. “Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA”. *Living Reviews in Relativity* December 2018, 21:3



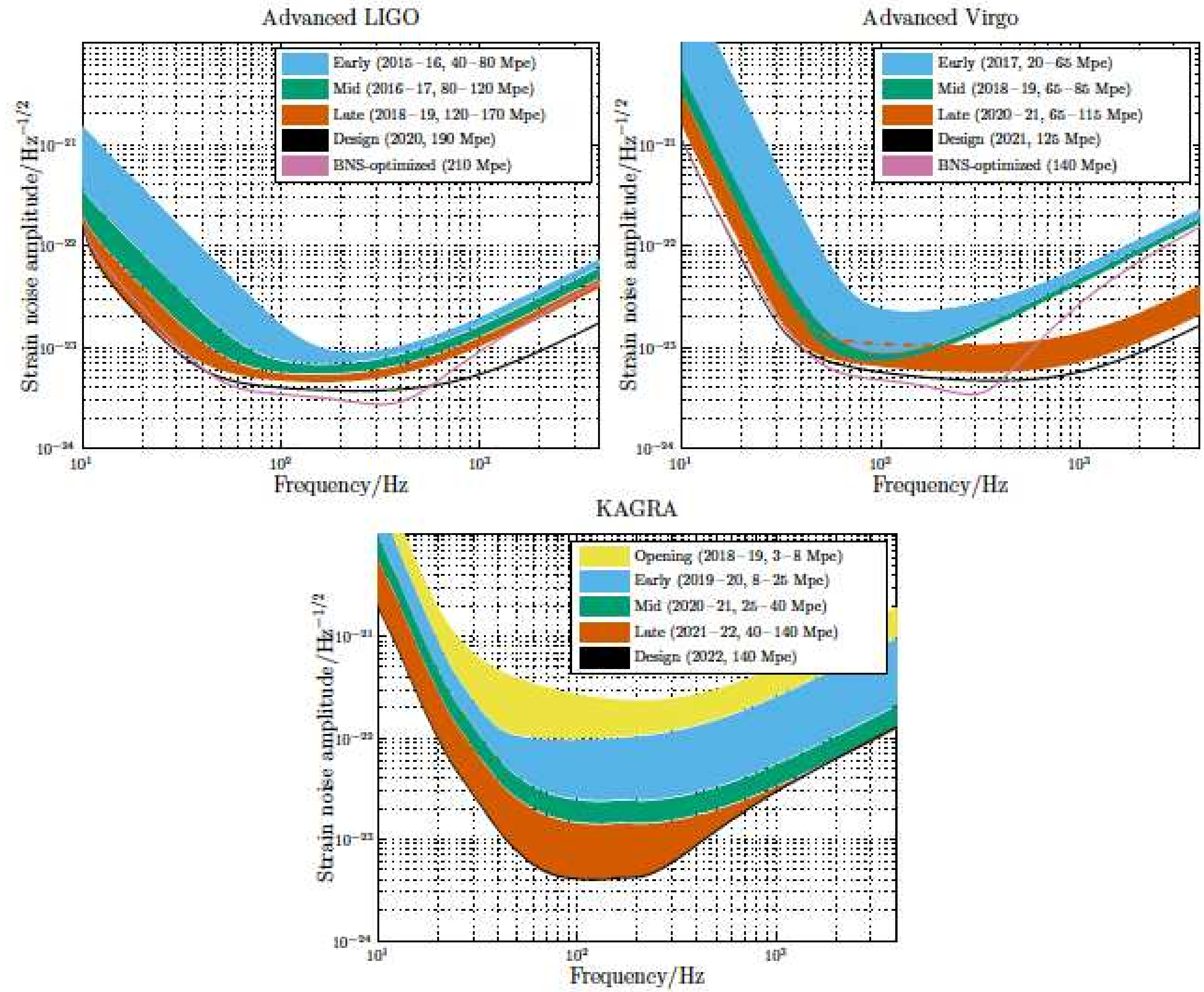



**Fig. 1** Regions of aLIGO (*top left*), AdV (*top right*) and KAGRA (*bottom*) target strain sensitivities as a function of frequency. The binary neutron star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates

**How much can the sensitivity be improved by squeezing at 10GHz?**

**Mark Bocko and Gary Spetz (~600 MHz) got very good results in the 80's for resonant mass transducers.**

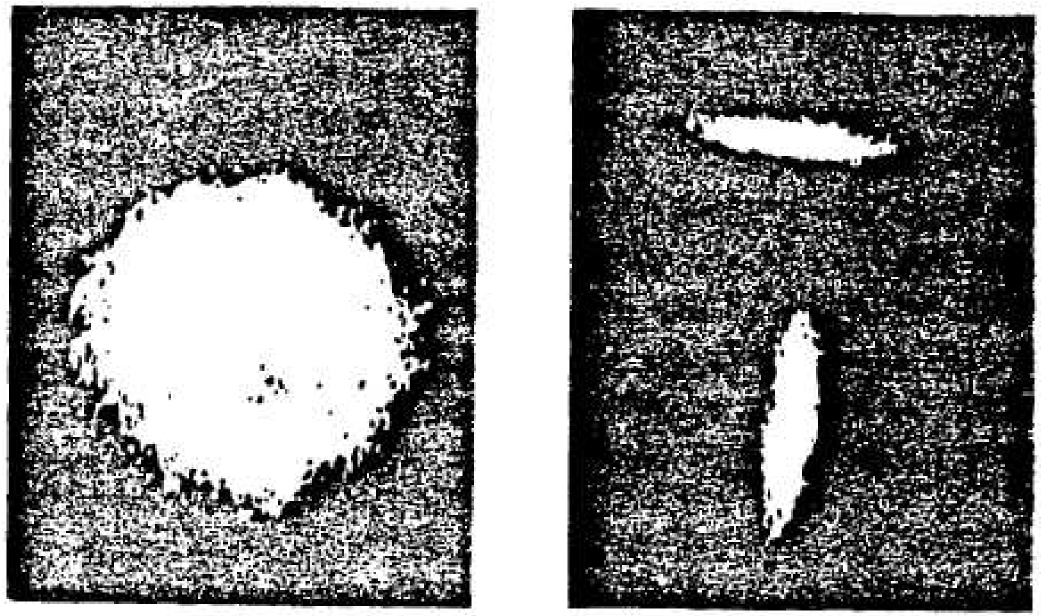


Fig. 2 Time-lapse display of the $X_1$, $X_2$ phase plane; left: No equeezing is evident, with $X_1$ and $X_2$ receiving equal noise; right: Squeezing is evident here, with the ellipse indicating squeezing of the injected noise. The two ellipses differ by a shift in the lock-in reference phase of 90°.

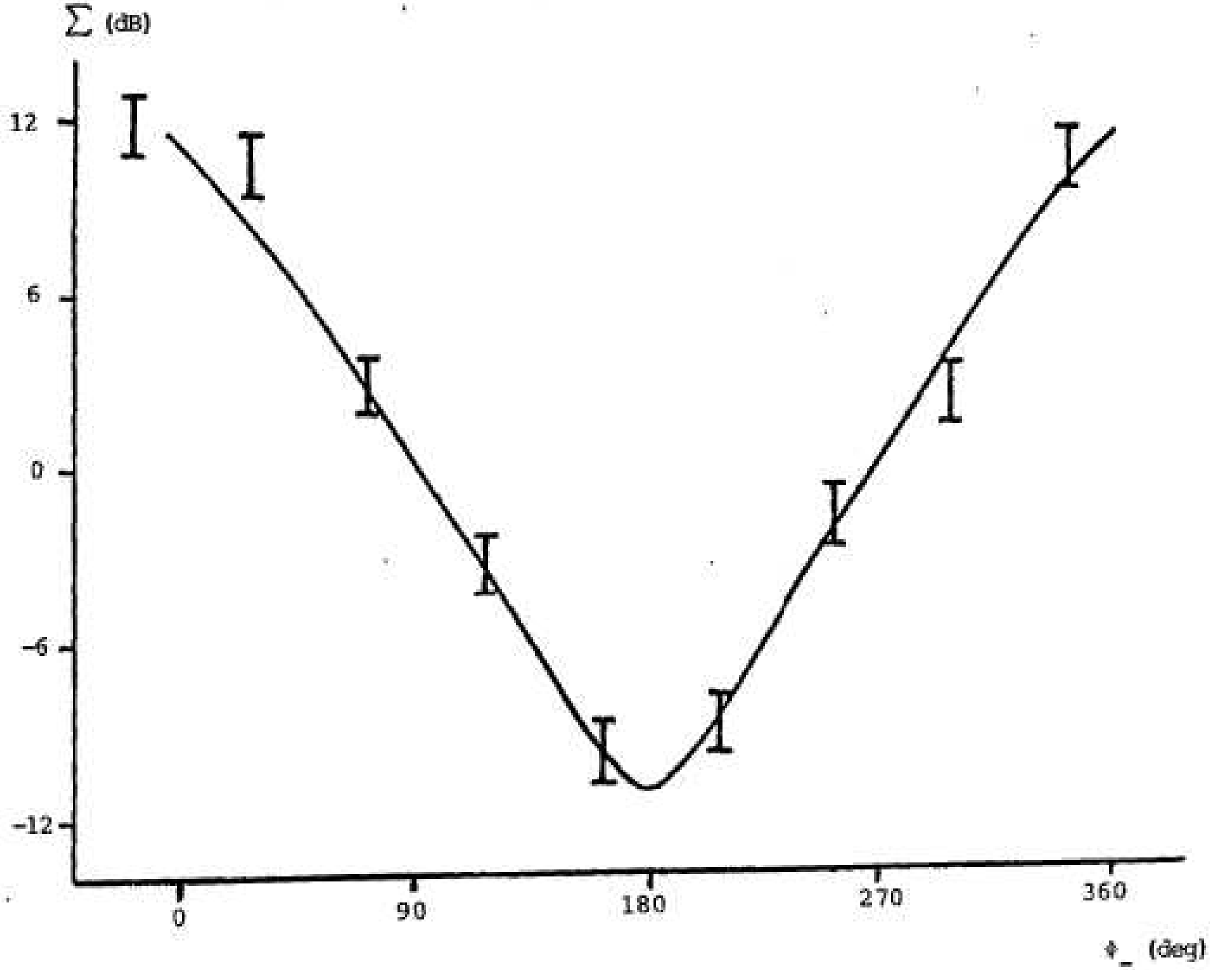
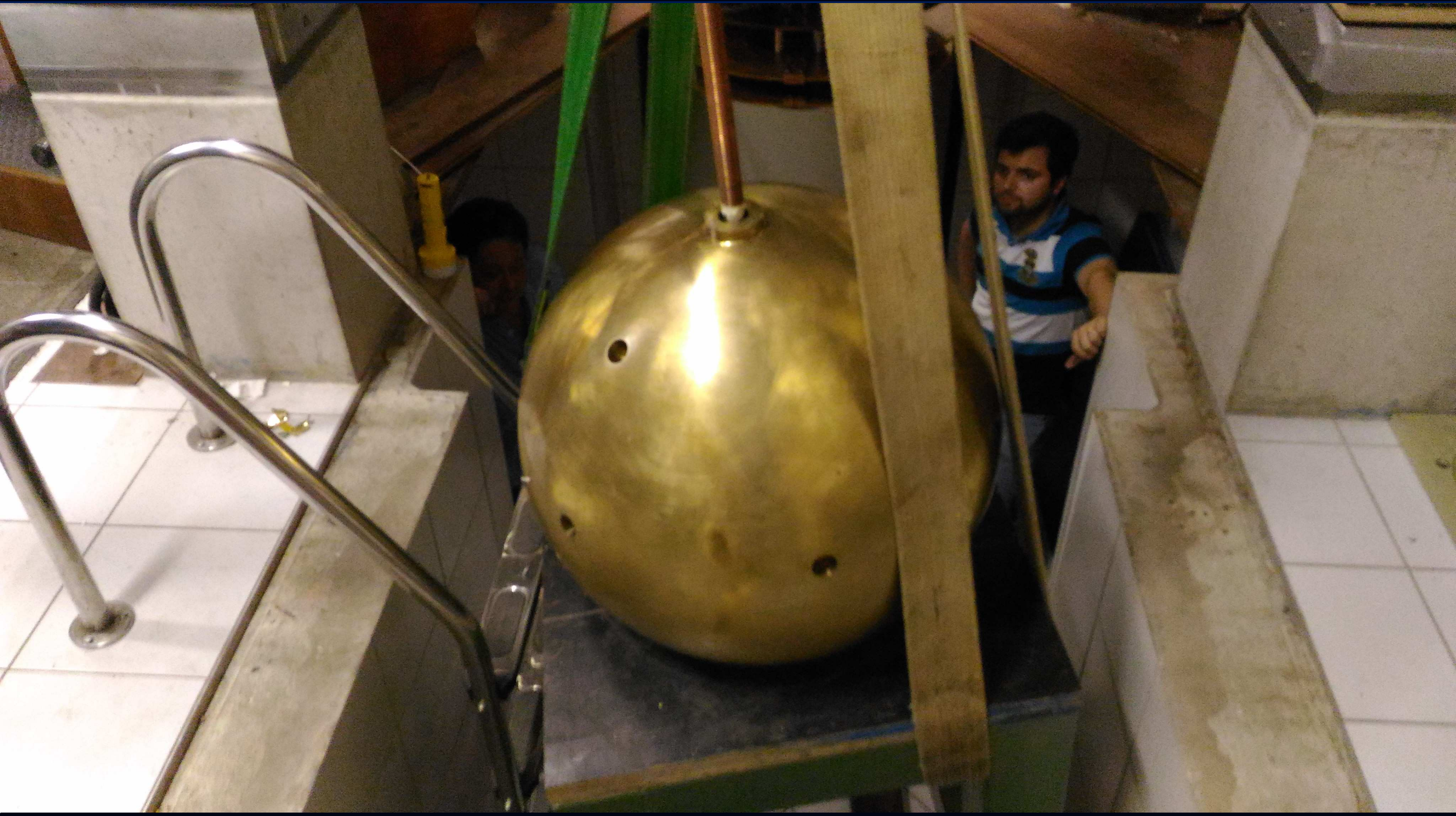


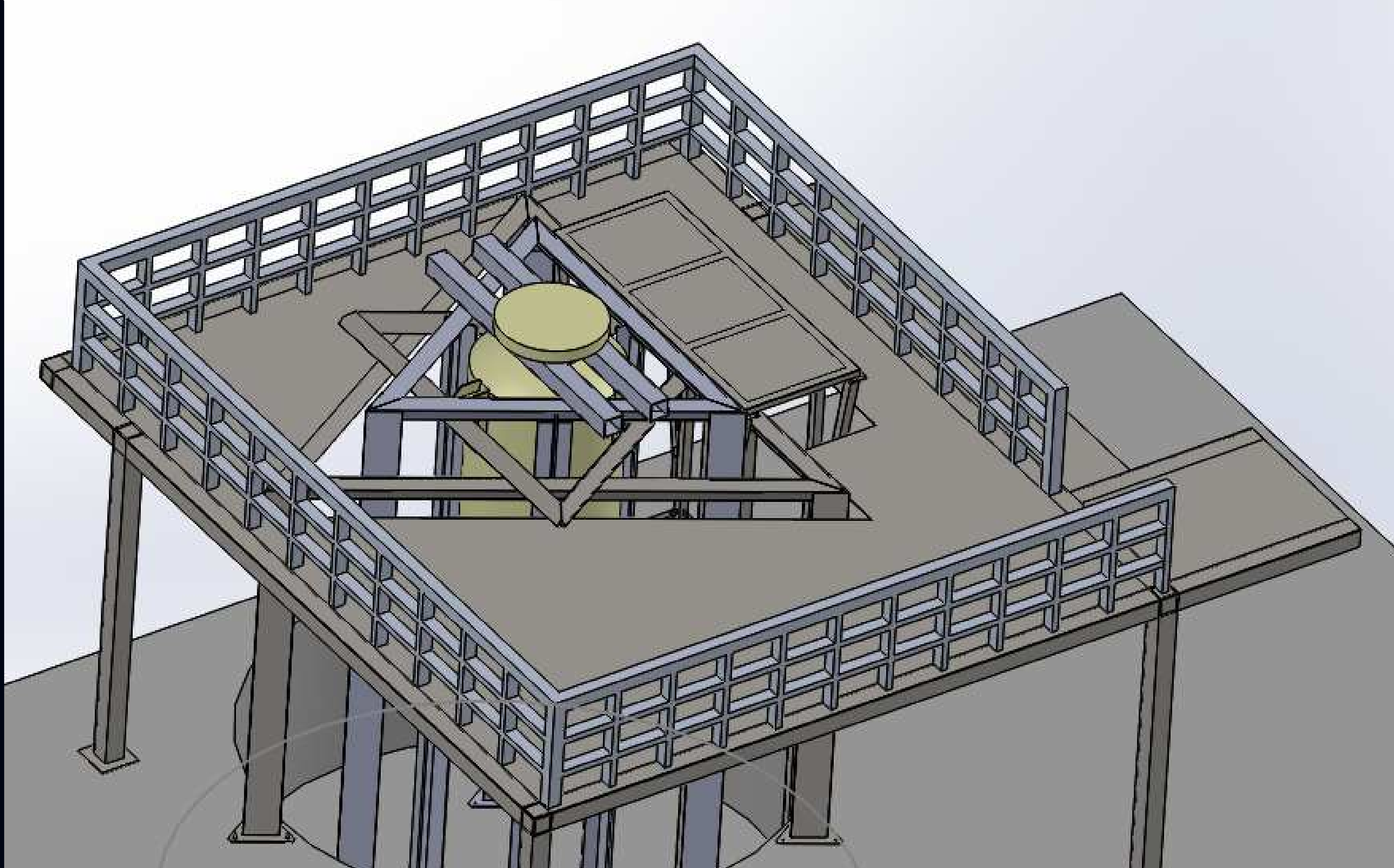

Figure 7.4 b) Squeezing as a Function of Lower Sideband Phase (Upper Sideband Phase = 0°)



This one see the sphere being removed from the USP site in 2016


**And placed in a truck to be transported to INPE in São José dos Campos**

We are going to use these three integrated pulse tubing to cool the sphere down inside our laboratory at INPE.



This time, instead to use a single concrete base on which everything is supported (sphere, vacuum chamber with the cryogenic liquids, synthesizers, amplifiers, turbomolecular pumps, etc) we are going to use many different metallic platforms, one for each system component (one for the sphere suspension, one for the vacuum chamber suspension, one for the electronics, and one people to walk around). The vacuum pumps would be grounded to the floor or walls, and long corrugate vacuum tubes would connect them to the vacuum chamber.

*Thematic Project Title:* **Design, development of instrumentation and data analysis of detectors and observatories for gravitational wave astronomy/astrophysics.**

**V.5 – STAFF INVOLVED IN THIS PROPOSAL (28 people)**

*Responsible Researcher:*

Prof. Odylio Denys de Aguiar (INPE, SP);

*Principal Researchers:*

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Prof. German Lugones (UFABC, SP),
Prof. Riccardo Sturani (IIP/UFRN, RN),
Prof. Cesar Augusto Costa (CGEE, DF);

*Associate Researchers:*

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Prof. José Carlos Neves Araújo (INPE, SP),
Prof. Joaquim José Barroso (ITA, SP),
Prof. Rubens de Melo Marinho Júnior (ITA, SP),
Prof. Samuel Rocha de Oliveira (UNICAMP, SP),
Prof. Márcio E. S. Alves (UNESP São José dos Campos, SP),
Prof. Rogério Moraes Oliveira (INPE, SP),
Prof. Carlos Frajuca (IF-SP, SP),
Prof. Kilder Leite Ribeiro (UFRB, BA),
Prof. Fábio da Silva Bortoli (IF-SP, SP),
Prof. César H. Lenzi (ITA, SP),
Prof. Dr. Sérgio Turano de Souza (FATEC Itaquera, SP),
Dr. Xavier Gratens (IFUSP, SP),
Dr. Elvis Camilo Ferreira (Editora Poliedro, SP)
Dr. Carlos Filipe da Silva Costa;

*Fellowship holders:*

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MSc. Tábata Aira Ferreira (CAPES/INPE, SP),
Ana Beatriz Cordeiro Costa (FAPESP/INPE, SP),
Dr. Vincenzo Liccardo (FAPESP/INPE, SP);

*Technical support:*

Engineer Dr. Cesar Strauss (INPE, SP),
Technician Marcos André Okada (INPE, SP),
Technician Lázaro Aparecido Pires de Camargo (INPE, SP),
Technician Alan Braga Cassiano (INPE, SP).

# We are proposing a thematic project

**THERE ARE 51 PAPERS ASSOCIATED TO THE SCHENBERG PROJECT (IN 20 YEARS). THE LAST 12 ARE THE FOLLOWING:**

DA SILVA BORTOLI, FABIO ; FRAJUCA, Carlos ; MAGALHAES, NADJA S. ; AGUIAR, ODYLIO D. ; DE SOUZA, SERGIO TURANO . On the Cabling Seismic Isolation for the Microwave Transducers of the Schenberg Detector. BRAZILIAN JOURNAL OF PHYSICS, v. 1, p. 1-7, 2018.

CARVALHO, N C ; BOURHILL, J ; Tobar, M E ; Aguiar, O D . Sensitivity characterisation of a parametric transducer for gravitational wave detection through optical spring effect. CLASSICAL AND QUANTUM GRAVITY, v. 34, p. 175001, 2017.

DA SILVA BORTOLI, FABIO ; FRAJUCA, Carlos ; DE SOUSA, SERGIO TURANO ; DE WAARD, Arlette ; MAGALHAES, NADJA SIMAO ; DE AGUIAR, ODYLIO DENYS . On the Massive Antenna Suspension System in the Brazilian Gravitational Wave Detector SCHENBERG. Brazilian Journal of Physics (Impresso), v. 46, p. 308-315, 2016.

FRAJUCA, C ; BORTOLI, F S ; MAGALHÃES, N S ; AGUIAR, O D . Thermal connection and vibrational isolation: an elegant solution for two problems. Journal of Physics. Conference Series (Print), v. 716, p. 012023, 2016.

LICCARDO, V. ; FRANÇA, E.K. ; AGUIAR, O.D. ; OLIVEIRA, R.M. ; RIBEIRO, K.L. ; SILVA, M.M.N.F. . Study of the effect of NbN on microwave Niobium cavities for gravitational wave detectors. Journal of Instrumentation, v. 11, p. P07004-P07004, 2016.

OLIVEIRA, NEI F. ; AGUIAR, ODYLIO D. . The Mario Schenberg Gravitational Wave Antenna. Brazilian Journal of Physics (Impresso), v. 46, p. 596-603, 2016.
Citations:1|1

DE PAULA, L.A.N. ; FERREIRA, E.C. ; CARVALHO, N.C. ; AGUIAR, O.D. . High sensitivity niobium parametric transducer for the Mario Schenberg gravitational wave detector. Journal of Instrumentation, v. 10, p. P03001-P03001, 2015.
Citations:3|4

DA SILVA COSTA, CARLOS FILIPE ; STRAUSS, CESAR ; COSTA, Cesar Augusto ; AGUIAR, Odylio Denys . Timestamp Reliability of the Schenberg Gravitational Wave Detector Data Acquisition System. IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, v. 64, p. 1-1, 2015.

Da SILVA COSTA, C F ; AGUIAR, O D . Spherical gravitational wave detectors: MiniGRAIL and Mario Schenberg. Journal of Physics. Conference Series (Online), v. 484, p. 012012, 2014.
Citations:1

DA SILVA COSTA, C.F. ; FAUTH, A.C. ; PEREIRA, L.A.S. ; AGUIAR, O.D. . The cosmic ray veto system of the Mario Schenberg gravitational wave detector. Nuclear Instruments & Methods in Physics Research. Section A, Accelerators, Spectrometers, Detectors and Associated Equipment (Print), v. 752, p. 65-70, 2014.
Citations:1|1

DE PAULA, L A N ; FURTADO, S R ; AGUIAR, O D ; N F OLIVEIRA JR ; CASTRO, P J ; BARROSO, J J . High-Q superconducting niobium cavities for gravitational wave detectors. Journal of Instrumentation, v. 9, p. P10001-P10001, 2014.
Citations:3|3

COSTA, CARLOS FILIPE DA SILVA ; COSTA, César Augusto ; AGUIAR, Odylio Denys . Low-latency data analysis for the spherical detector Mario Schenberg. CLASSICAL AND QUANTUM GRAVITY, v. 31, p. 085012-085012-21, 2014.
Citations:3|4

**Thanks**

**for your attention !**

# Extra Slides

## In the past 20 years (1998-2017), at INPE:

- **15 doctorate thesis concluded on gravitational waves (gw):**

Herman, Kilder, Andrade, José Melo, César, Sérgio, Márcio Alves, Dennis, Cláudio Brandão, Eduardo, Edgard, Pedro, Carlos Eduardo, Enrique e Márcio Constâncio Jr. (LSC));

- **7 Master thesis concluded on gw by other students:**

Carla, Emílio, Cláudio, Natália, Patrick, Luiz Augusto, Fabrícia and Elvis (LSC).

In yellow, thesis related to experimental themes.

## In the past 26 years (1995-2017), at USP:

- **6 doctorate thesis concluded on gravitational waves:**

Velloso, Magalhaes, Frajuca, Sérgio, Fábio, Leandro.

All related to experimental themes.

Some other ~15 doctorate thesis on gravitational waves in other institutions in the country. Only three of them related to experimental themes (Fernanda, Lenzi, Stellati).

So a total of 16 doctorate thesis and 5 master thesis defended in the country, since 1992, related with gravitational wave detection technology.