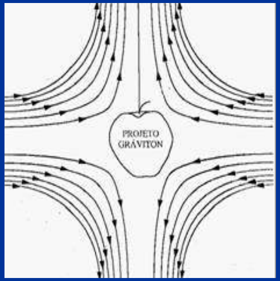
ONG / DAS / INPE

Linha de Pesquisa em **Astrofísica de Ondas Gravitacionais**, Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais



GRAVITON GROUP

LSC LIGO Scientific Collaboration

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Grupo Gráviton

São José dos Campos, 04 de Abril de 2017

CAPES · FAPESP · CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

Grupo Experimental da ONG/DAS/INPE (6)

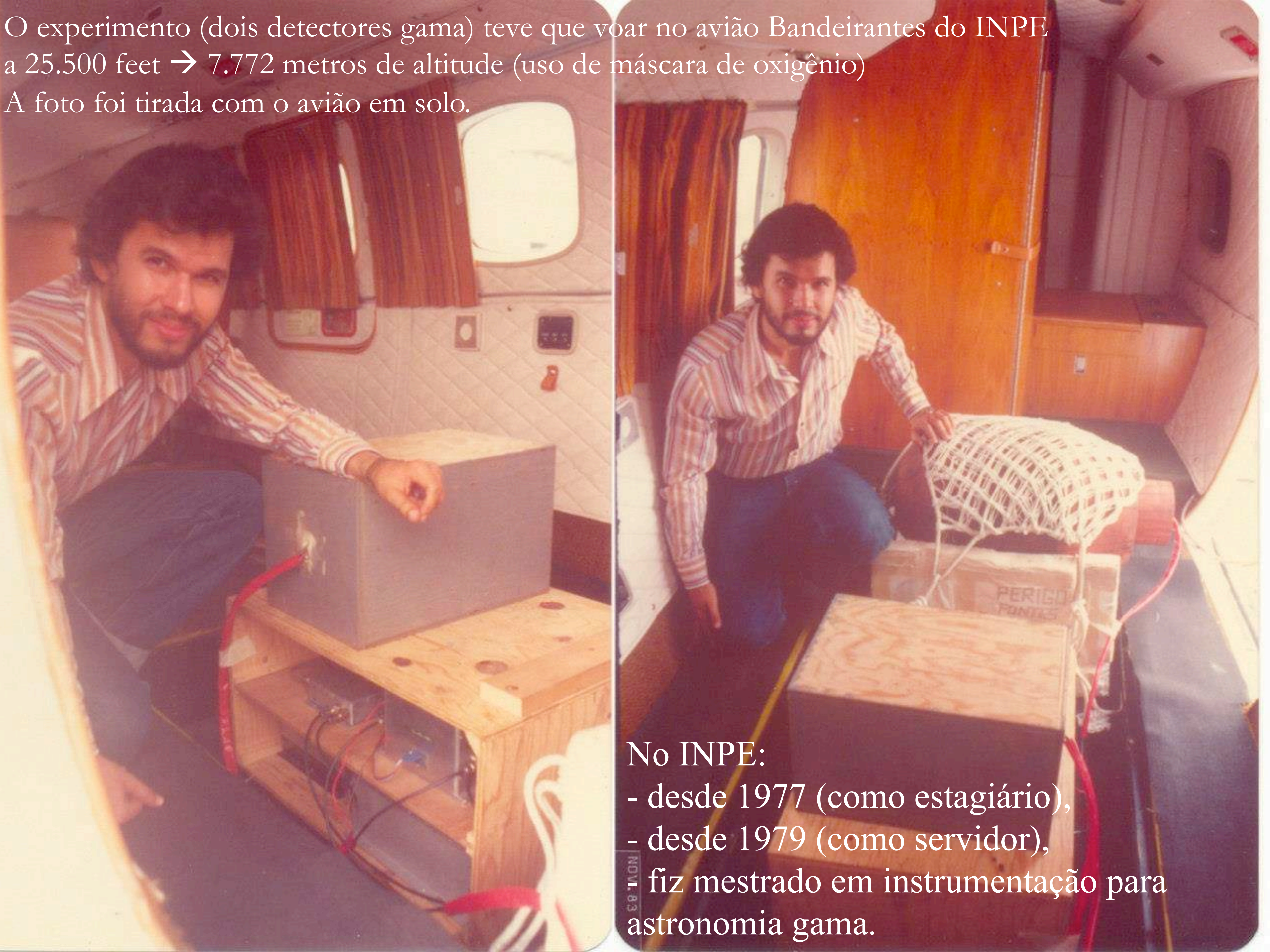
Odylio, Marcos

César

Márcio, Elvis, Tábata

Allan, Felipe, Carlos, Guilherme

Diego


O experimento (dois detectores gama) teve que voar no avião Bandeirantes do INPE
a 25.500 feet → 7.772 metros de altitude (uso de máscara de oxigênio)
A foto foi tirada com o avião em solo.
PERIGO
No INPE:
- desde 1977 (como estagiário),
- desde 1979 (como servidor),
- fiz mestrado em instrumentação para astronomia gama.

Fui em agosto de 1984 para a LSU (para fazer doutorado).

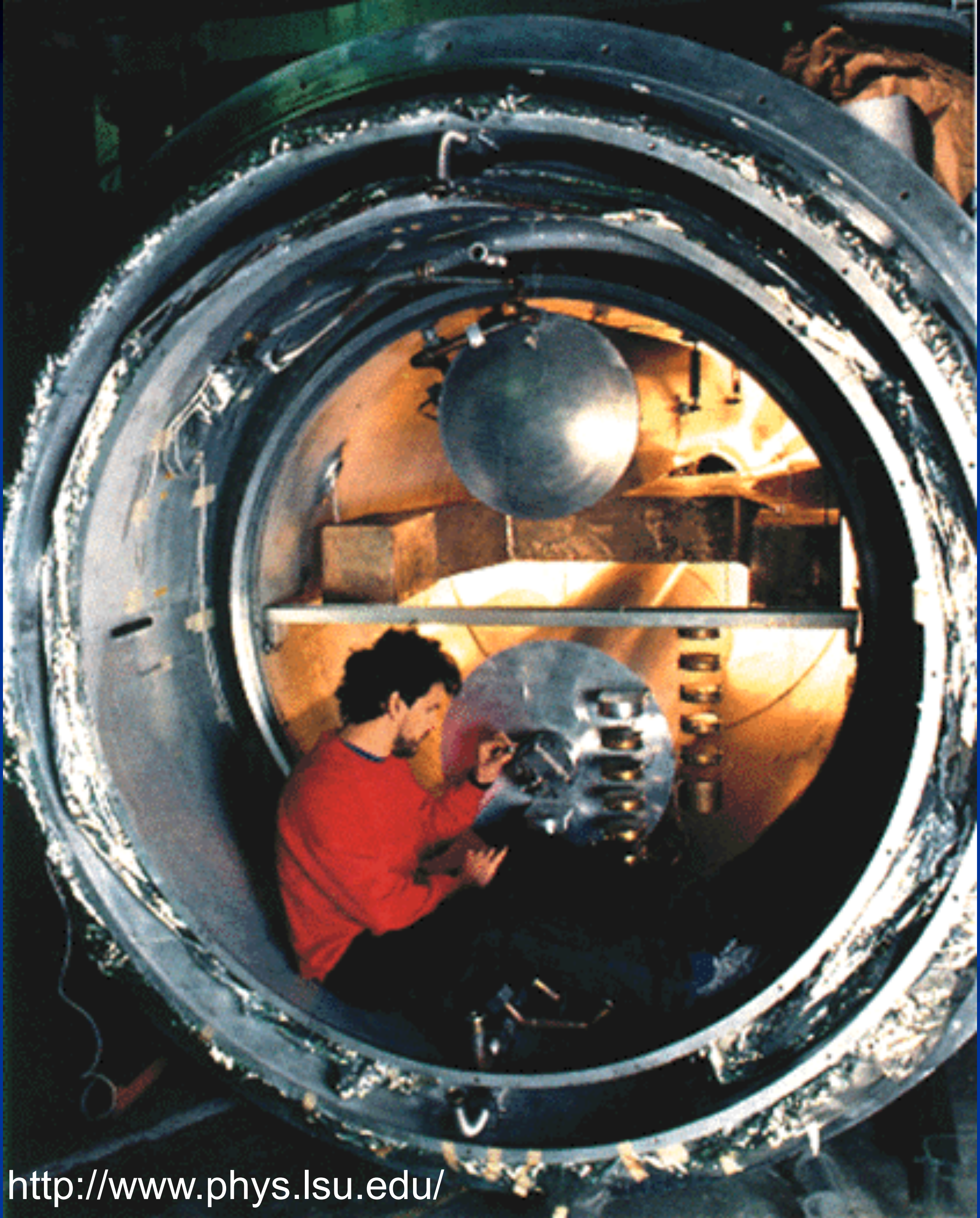
Na área de detecção de ondas gravitacionais desde maio de 1986 (após o ‘Qualifying’).

LSU (ALLEGRO)

2ª geração de barras

Cilíndrico
- 269 ºC

h ~ 5 x 10^{-19}



Astron. Astrophys. 216, 325–332 (1989)

30 authors from 9 institutions

ASTRONOMY AND ASTROPHYSICS

First gravity wave coincidence experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford

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Summary. The results of a coincidence search for short bursts of gravitational radiation with cryogenic resonant-mass detectors are reported. No significant excess of coincidences at zero time delay were found. The data have been used to set an improved observational upper limit on the flux of impulsive gravitational waves that may be impinging on the Earth.

Key words: gravitational waves – detectors, gravitational waves – coincidence experiment

employs a resonant capacitive transducer (Rapagnani, 1982) matched to a d.c. SQUID amplifier (Carelli, 1985).

The performance of the three detectors during this coincidence experiment did not reach the design goals or previously achieved levels by the Stanford detector in either sensitivity or in non-Gaussian disturbance level (Boughn, 1982). Despite this situation, the limit that we are able to set on the rate of gravity wave pulses impinging on the Earth is better than that set by any previous observations.

Inaugurada a Astronomia de Ondas Gravitacionais com a primeira detecção

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated

www.black-holes.org

http://link.aps.org/doi/10.1103/PhysRevX.6.041015

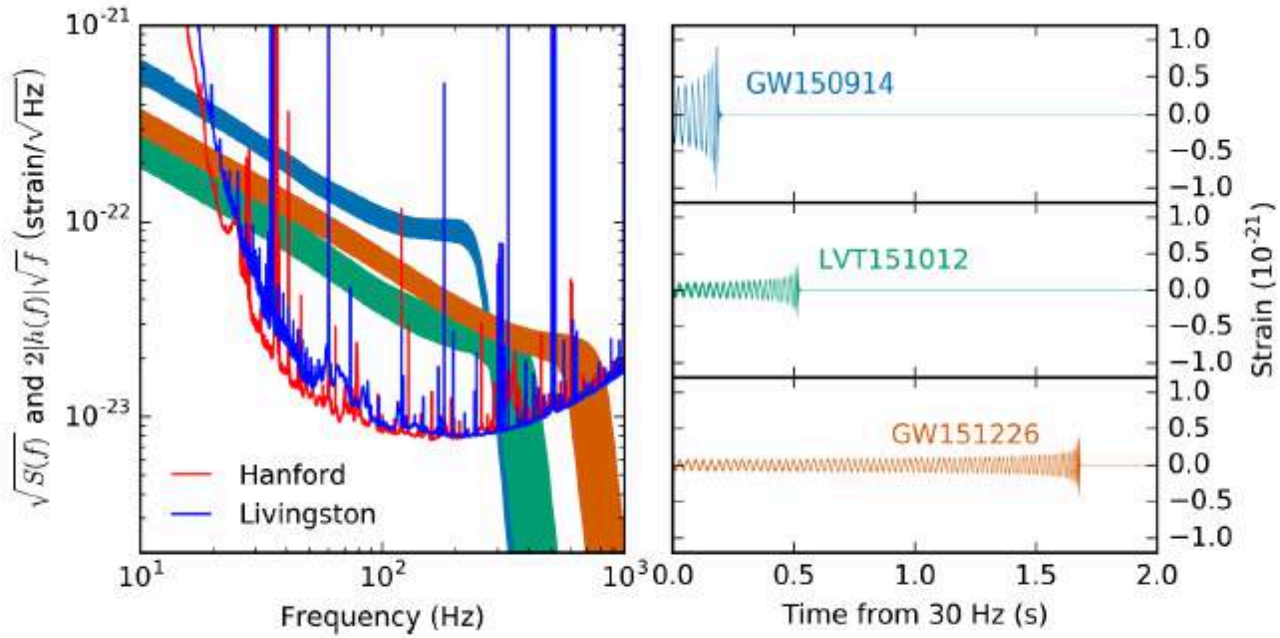

FIG. 1. Left panel: Amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226, and LVT151012 plotted so that the relative amplitudes can be related to the SNR of the signal (as described in the text). Right panel: Time evolution of the recovered signals from when they enter the detectors' sensitive band at 30 Hz. Both figures show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a nonprecessing spin waveform model [48].

http://link.aps.org/doi/10.1103/PhysRevX.6.041015

TABLE I. Details of the three most significant events. The false alarm rate, p-value, and significance are from the PyCBC analysis; the GstLAL results are consistent with this. For source parameters, we report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. The uncertainty for the peak luminosity includes an estimate of additional error from the fitting formula. The sky localization is the area of the 90% credible area. Masses are given in the source frame; to convert to the detector frame, multiply by $(1+z)$. The source redshift assumes standard cosmology [18].

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

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[1] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. **1**, 688 (1916).
[2] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. **1**, 154 (1918).
[3] P. R. Saulson, Gen. Relativ. Gravit. **43**, 3289 (2011).
[4] K. Schwarzschild, Sitzungsber. K. Preuss. Akad. Wiss. **1**,
[21] J. H. Taylor and J. M. Weisberg, Astrophys. J. **253**, 908 (1982).
[22] W. Press and K. Thorne, Annu. Rev. Astron. Astrophys. **10**, 335 (1972).
[23] J. Weber, Phys. Rev. **117**, 306 (1960).
[24] P. Astone *et al.*, Phys. Rev. D **82**, 022003 (2010).
[25] M. E. Gertsenshtein and V. I. Pustovoit, Sov. Phys. JETP **16**, 433 (1962).
[26] G. E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. **10**, 2495 (1971).
[27] R. Weiss, Electromagnetically coupled broadband gravitational antenna, Quarterly Report of the Research Laboratory for Electronics, MIT Report No. 105, 1972, https://dcc.ligo.org/LIGO-P720002/public/main.
[28] R. W. P. Drever, in *Gravitational Radiation*, edited by N. Deruelle and T. Piran (North-Holland, Amsterdam, 1983), p. 321.
[29] R. W. P. Drever, F. J. Raab, K. S. Thorne, R. Vogt, and R. Weiss, Laser Interferometer Gravitational-wave Observatory (LIGO) Technical Report, 1989, https://dcc.ligo.org/LIGO-M890001/public/main.
[30] A. Abramovici *et al.*, Science **256**, 325 (1992).
[31] A. Brillet, A. Giazotto *et al.*, Virgo Project Technical Report No. VIR-0517A-15, 1989, https://tds.ego-gw.it/ql/?c=11247.
[32] J. Hough *et al.*, Proposal for a joint German-British interferometric gravitational wave detector, MPQ Technical Report 147, No. GWD/137/JH(89), 1989, http://eprints.gla.ac.uk/114852.
[33] J. Aasi *et al.*, Classical Quantum Gravity **32**, 074001 (2015).
[34] F. Acernese *et al.*, Classical Quantum Gravity **32**, 024001 (2015).
[35] C. Affeldt *et al.*, Classical Quantum Gravity **31**, 224002 (2014).

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Research paper

Cryogenically cooled ultra low vibration silicon mirrors for gravitational wave observatories

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ABSTRACT

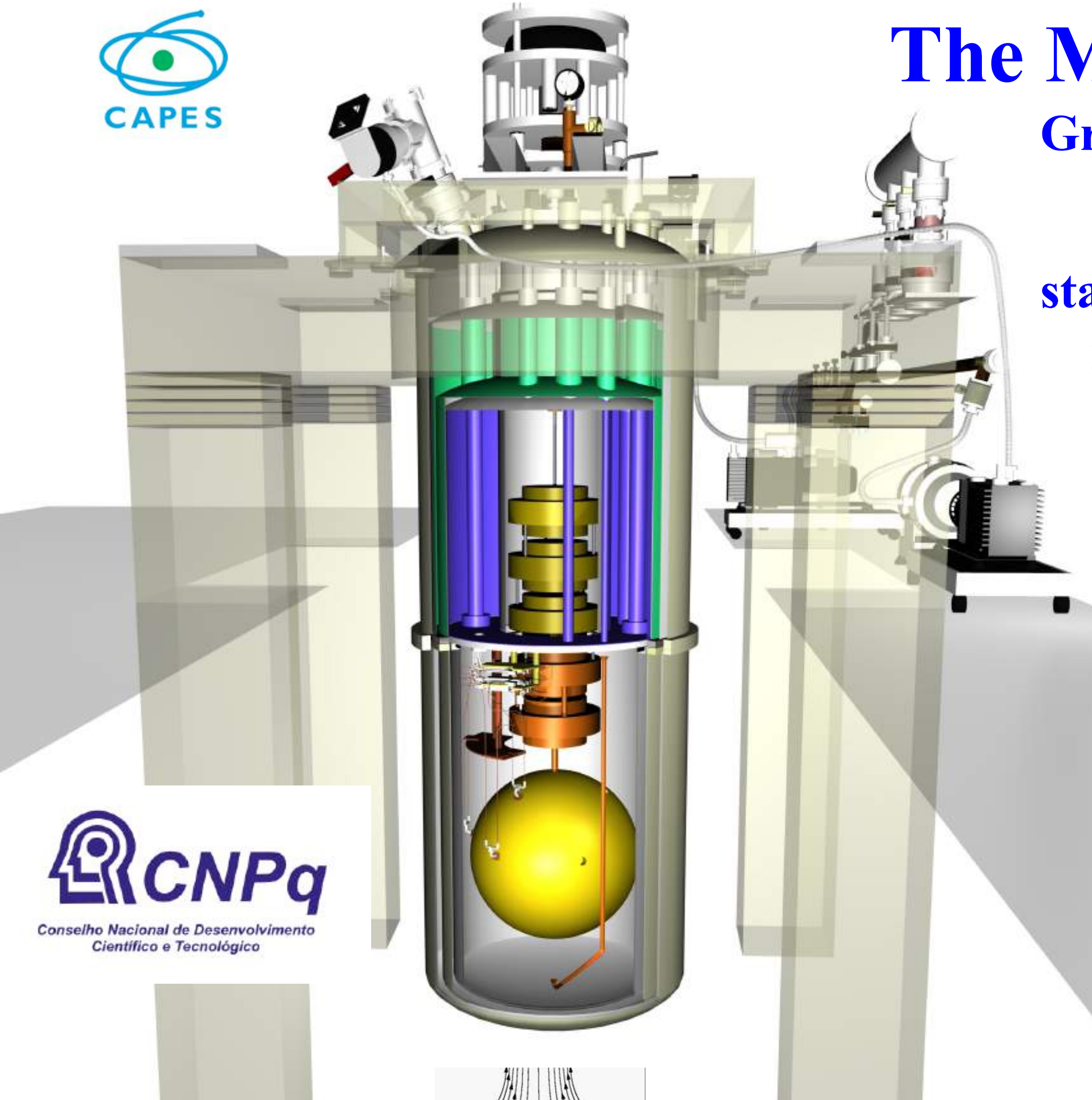
Interferometric gravitational wave observatories recently launched a new field of gravitational wave astronomy with the first detections of gravitational waves in 2015. The number and quality of these detections is limited in part by thermally induced vibrations in the mirrors, which show up as noise in these interferometers. One way to reduce this thermally induced noise is to use low temperature mirrors made of high purity single-crystalline silicon. However, these low temperatures must be achieved without increasing the mechanical vibration of the mirror surface or the vibration of any surface within close proximity to the mirrors. The vibration of either surface can impose a noise inducing phase shift on the light within the interferometer or physically push the mirror through oscillating radiation pressure. This paper proposes a system for the Laser Interferometric Gravitational-wave Observatory (LIGO) to achieve

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

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GRAVITON GROUP

USP

FAPESP

Status Report of the Schenberg Gravitational Wave Antenna

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Study of the effect of NbN on microwave Niobium cavities for gravitational wave detectors

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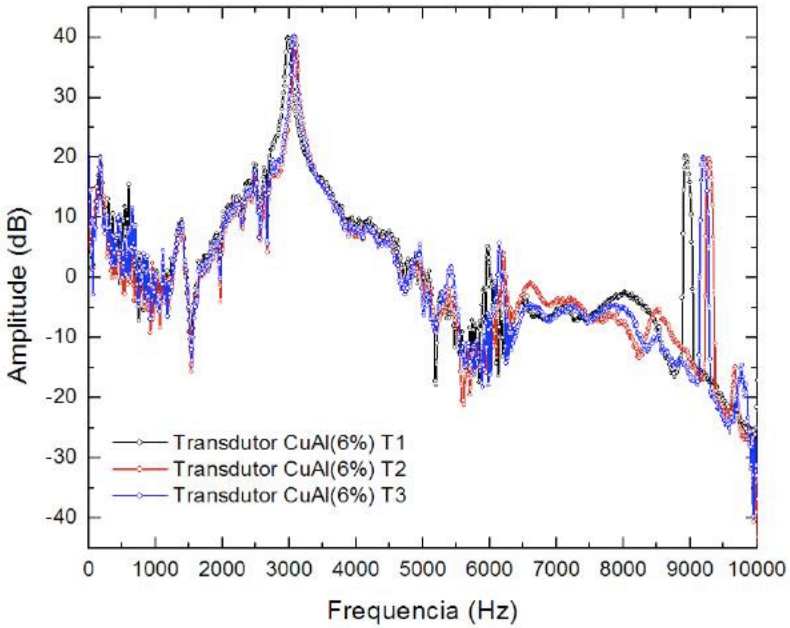
Abstract: Superconducting reentrant cavities may be used in parametric transducers for resonant-mass gravitational wave detectors. When coupled to a spherical resonant antenna, transducers will monitor its mechanical quadrupolar modes, working as a mass-spring system. In this paper

The three initial transducers:

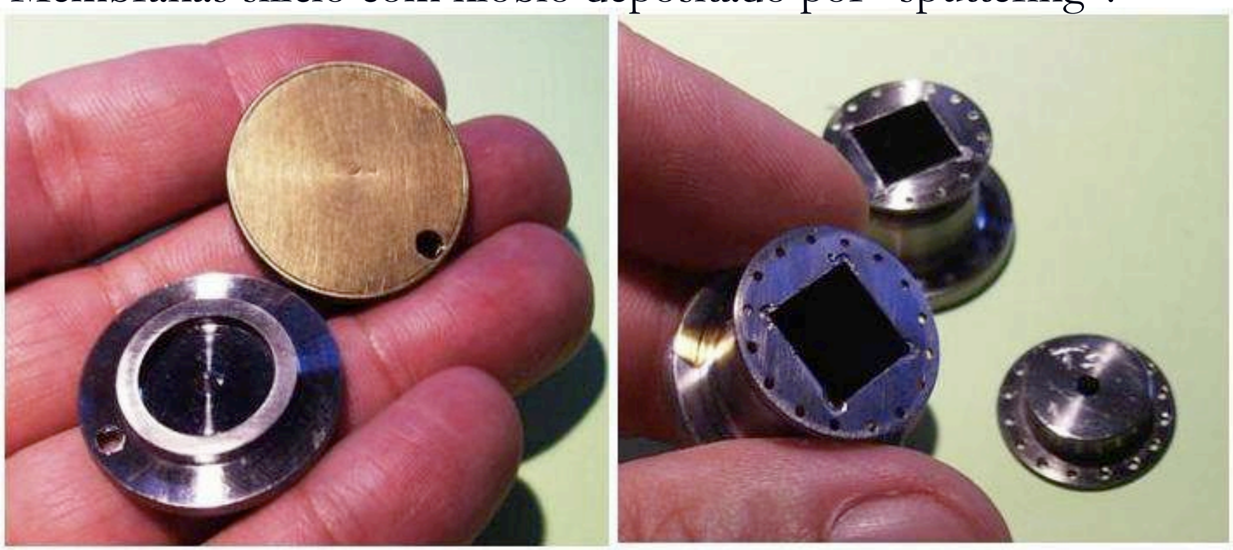
$Q_e \sim 10^4$

First design

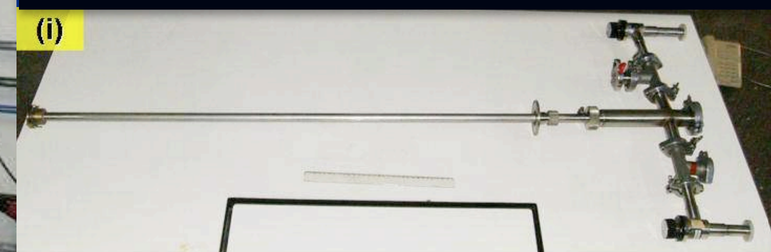
Medidas das frequências de ressonância mecânica de três transdutores.

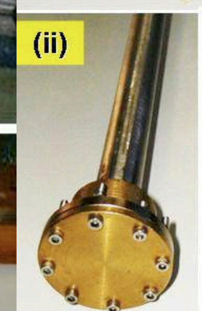


Membranas silício com nióbio depositado por "sputtering".

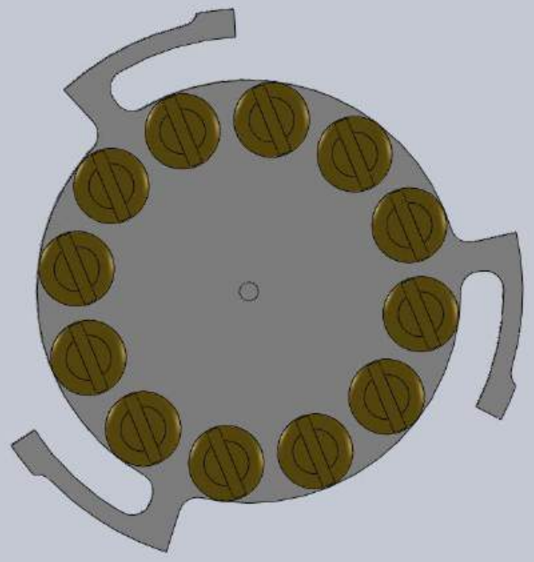


Foram medidos fatores de qualidade elétrica (Q_e) de várias cavidades reentrantes supercondutoras a 4.2 K, utilizando um "dewar" refrigerado a hélio líquido. Q_e tão altos quanto 300 k foram encontrados.

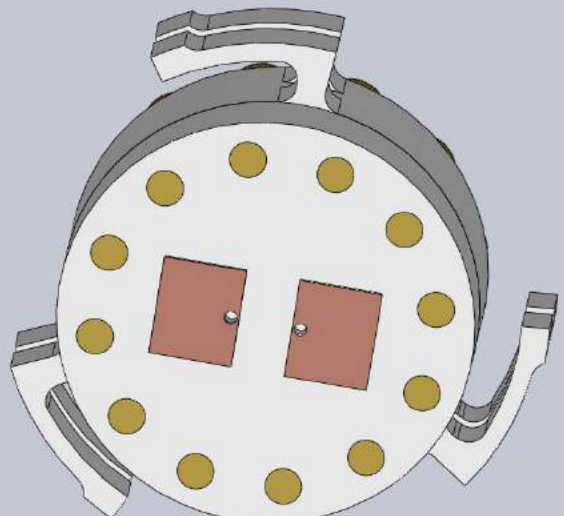




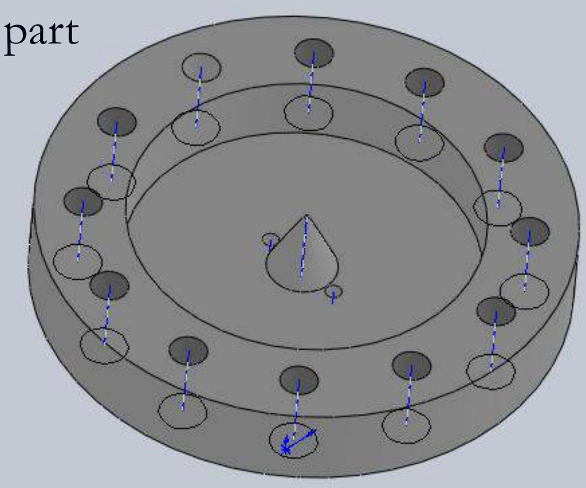
Aparato experimental para testar cavidades reentrantes supercondutoras dentro de um "dewar" refrigerado a hélio líquido.



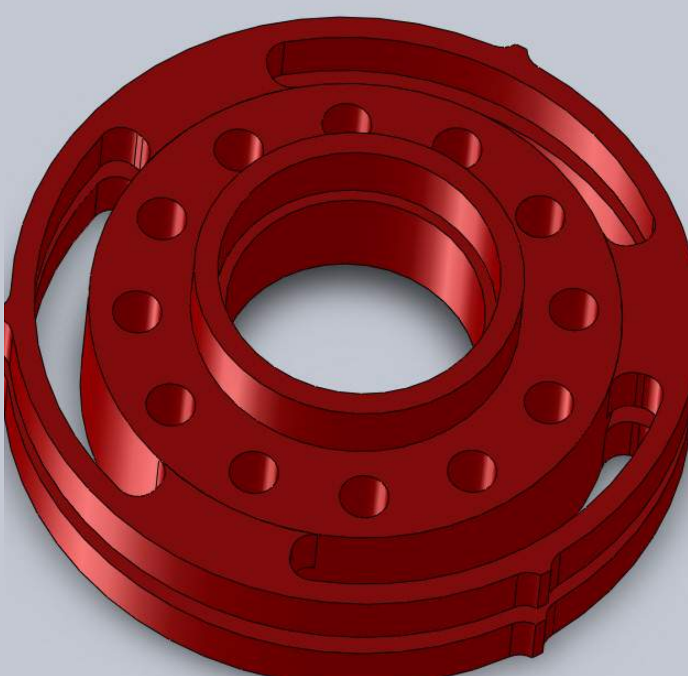
Third design



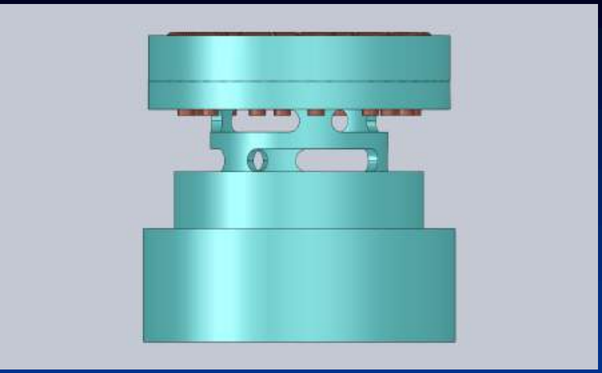
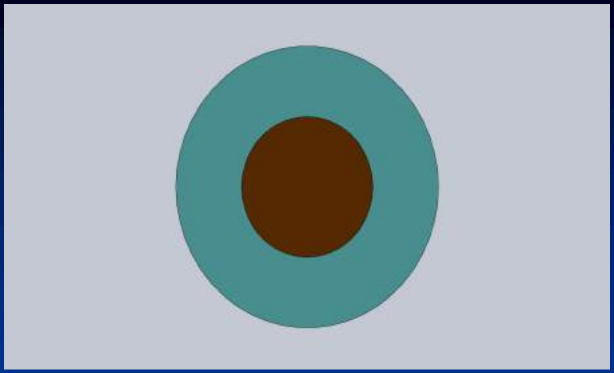
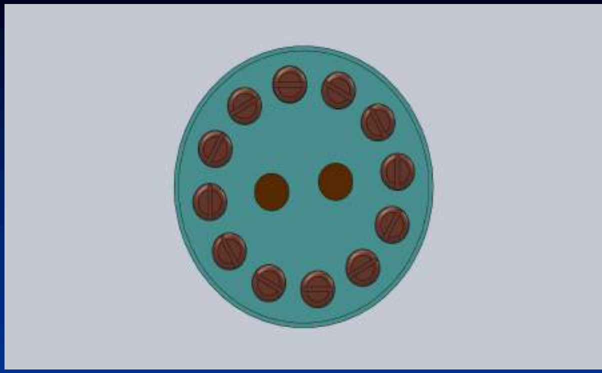
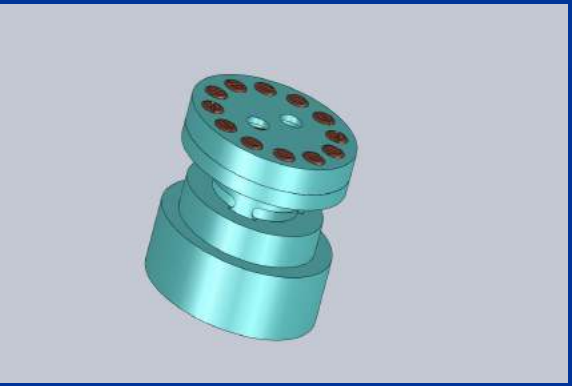
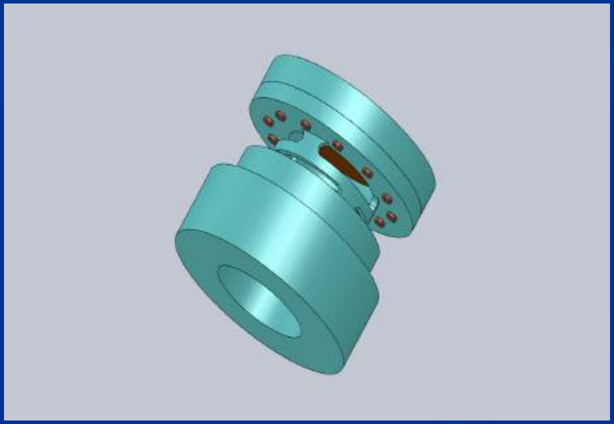
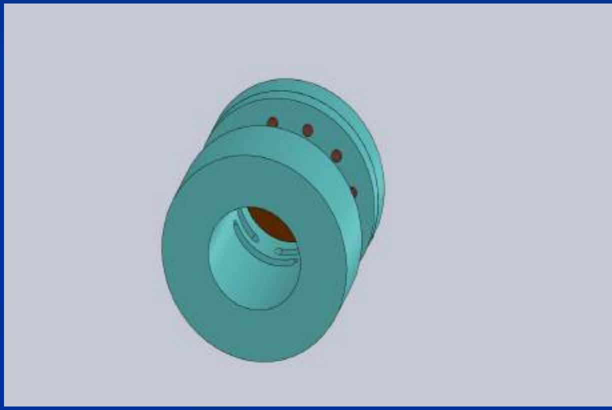
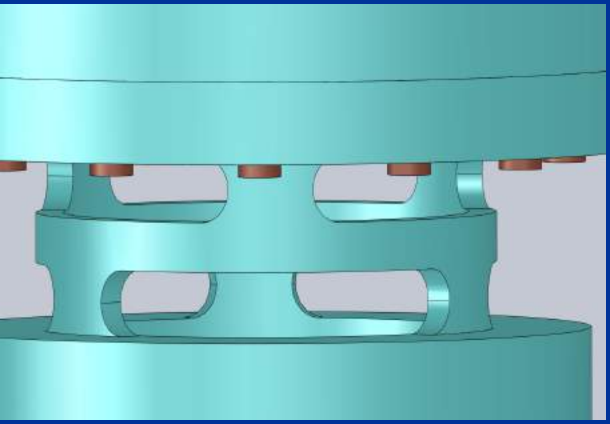
Alumina part



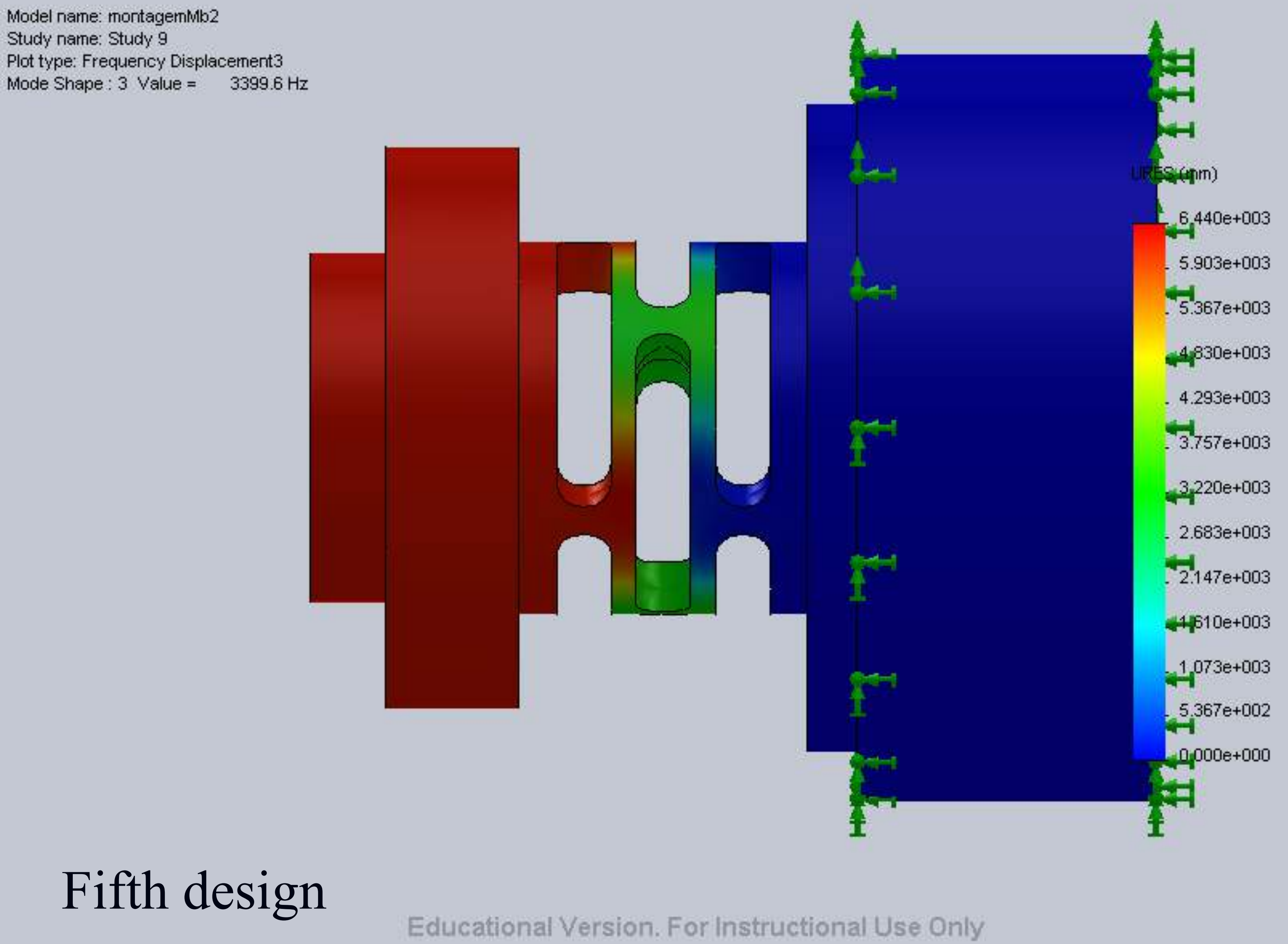
Fourth design



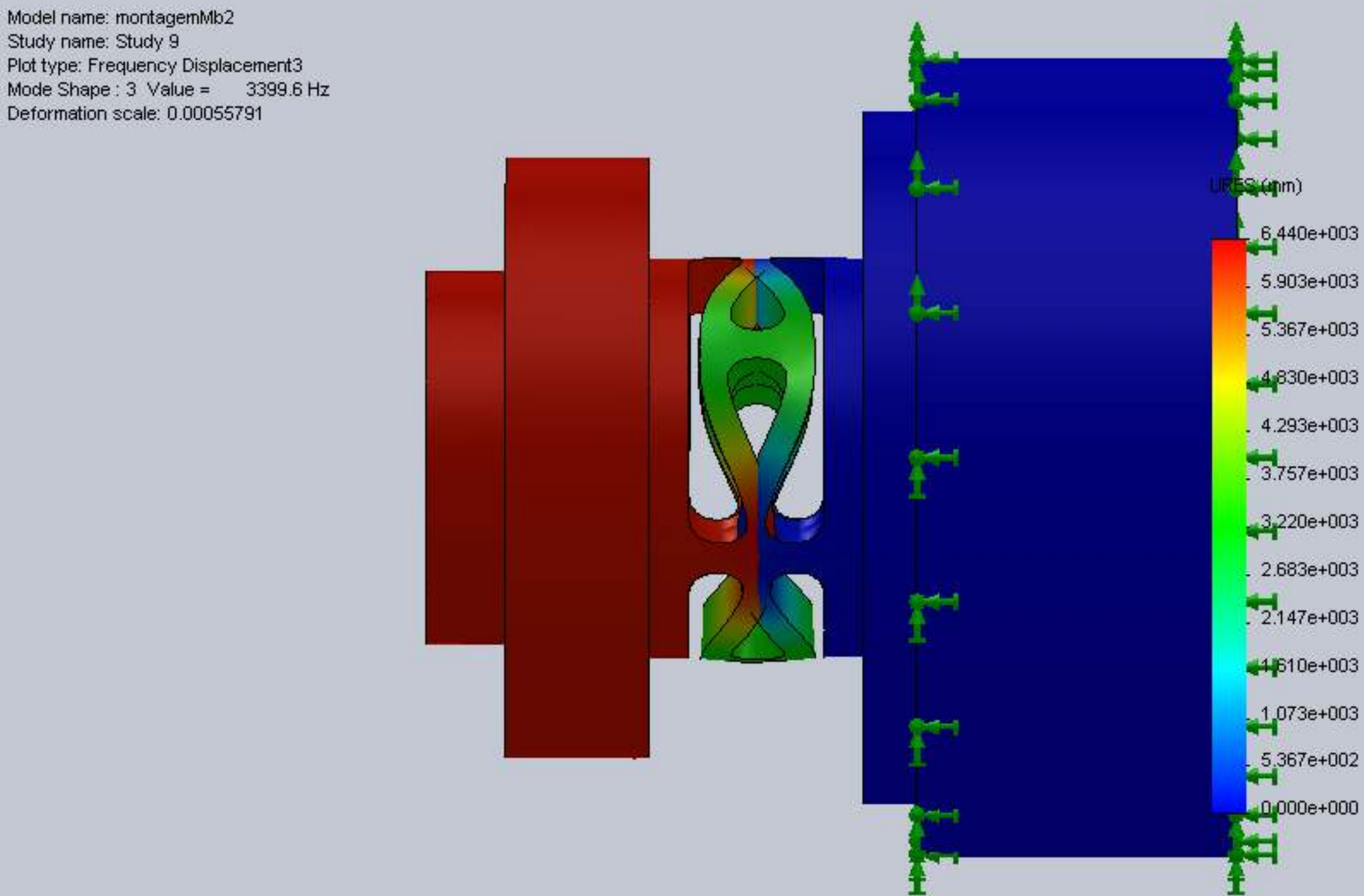
Niobium part

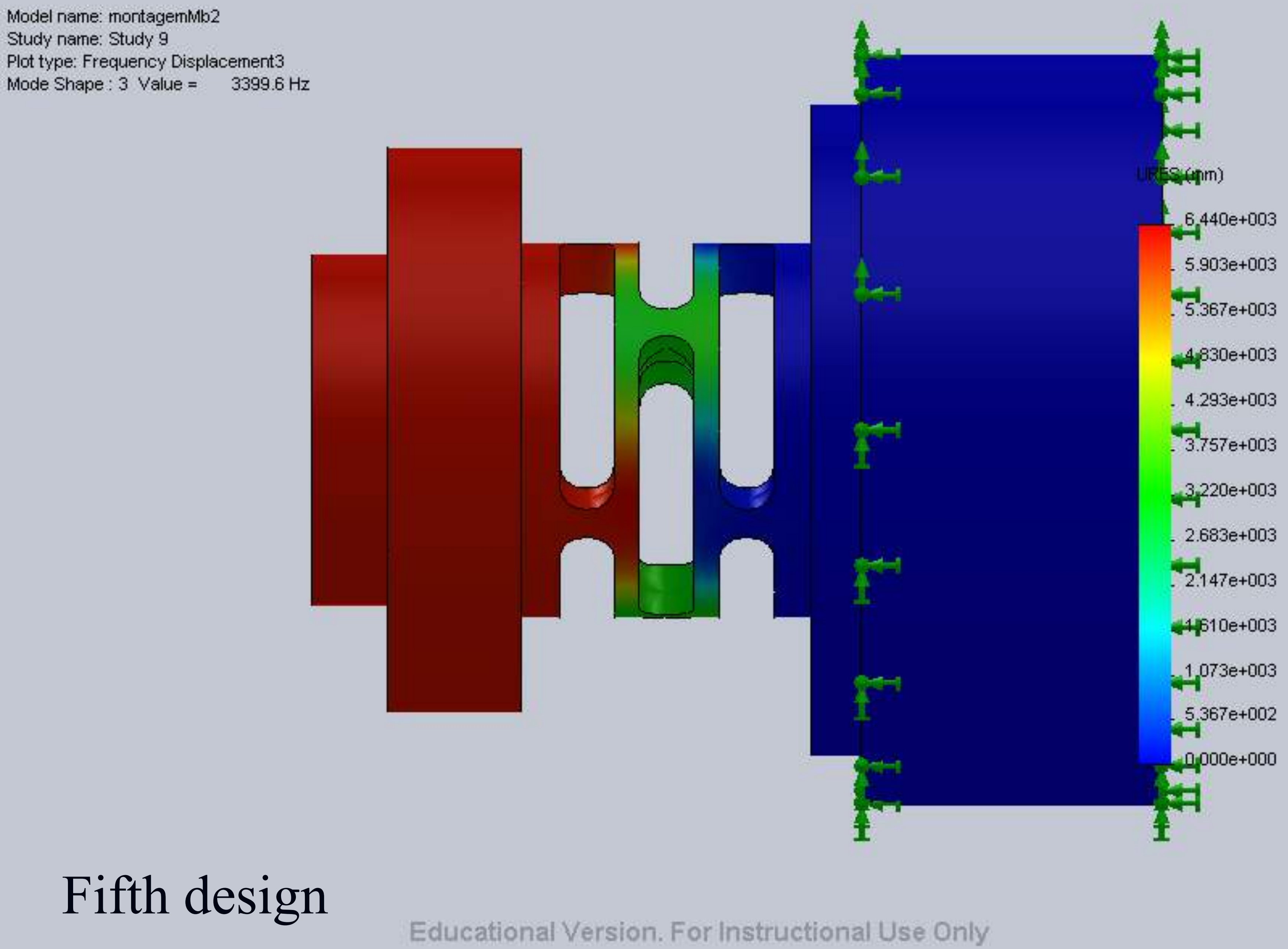
Fifth design



Fifth design

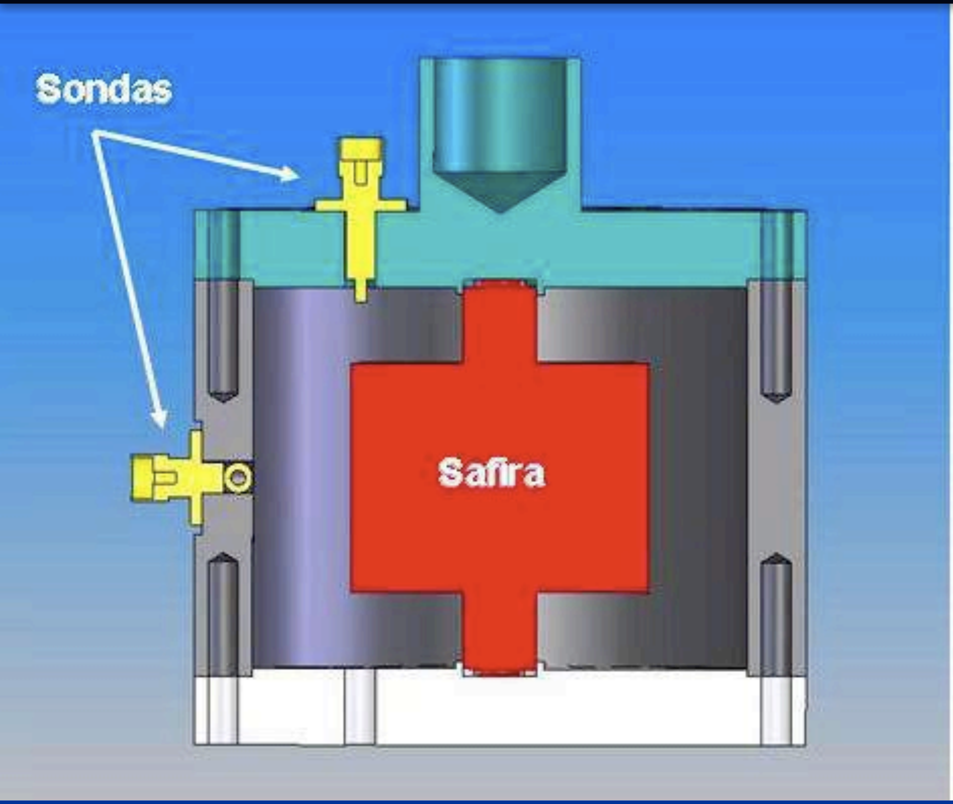


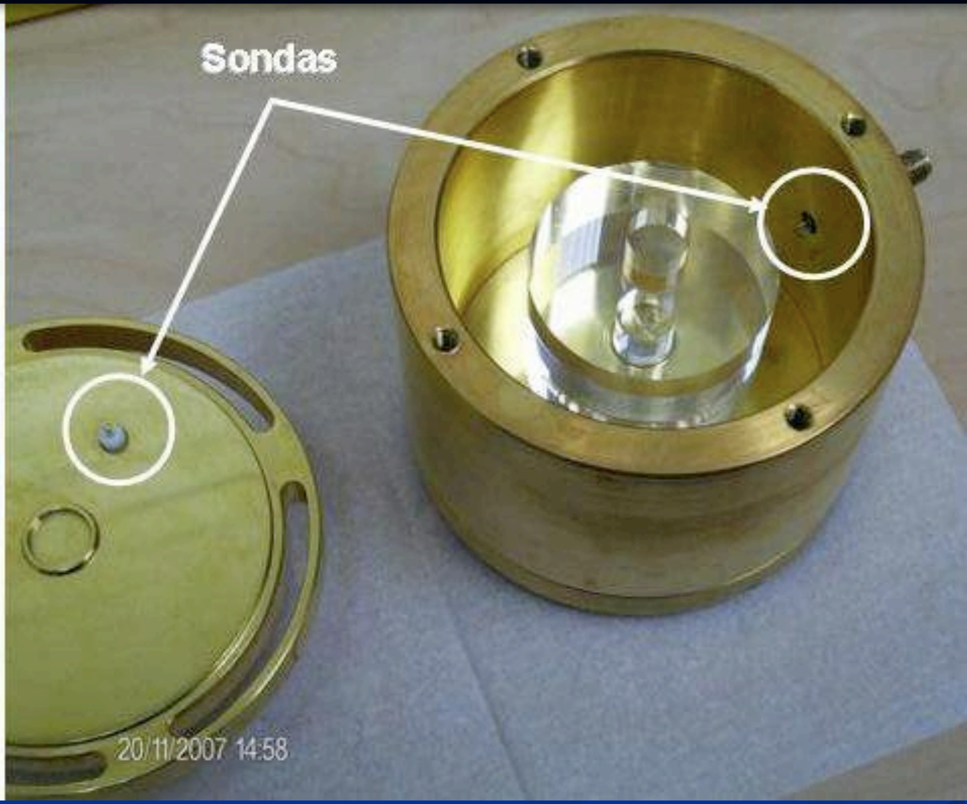
Fifth design



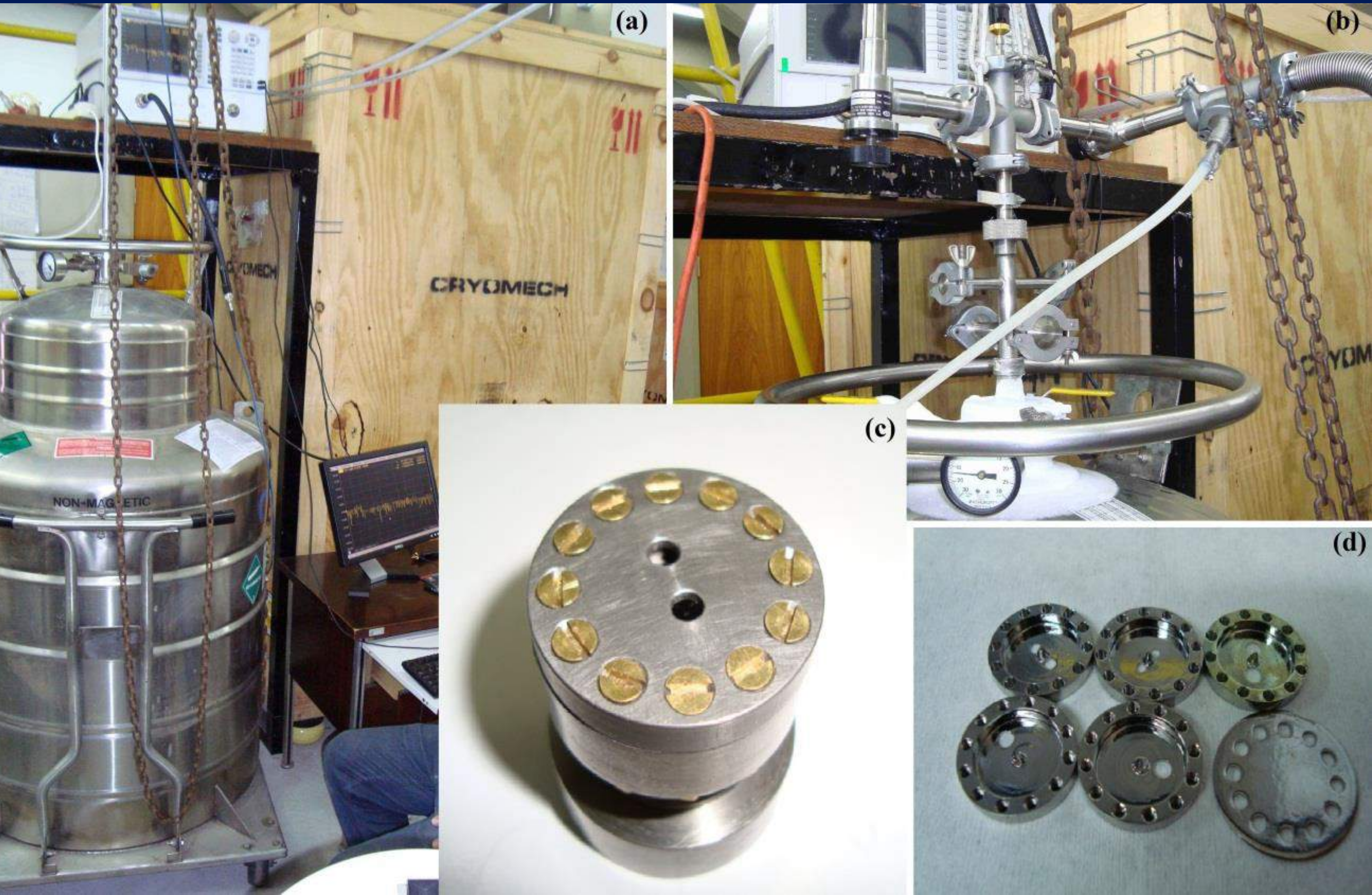
Fifth design

Desenvolvemos, em colaboração com o grupo australiano, um oscilador de safira que opera a 77 K e vai substituir, com melhor desempenho, os de titanato de bário atualmente utilizados.





Montagem de transdutores em sala limpa do INPE


(a)
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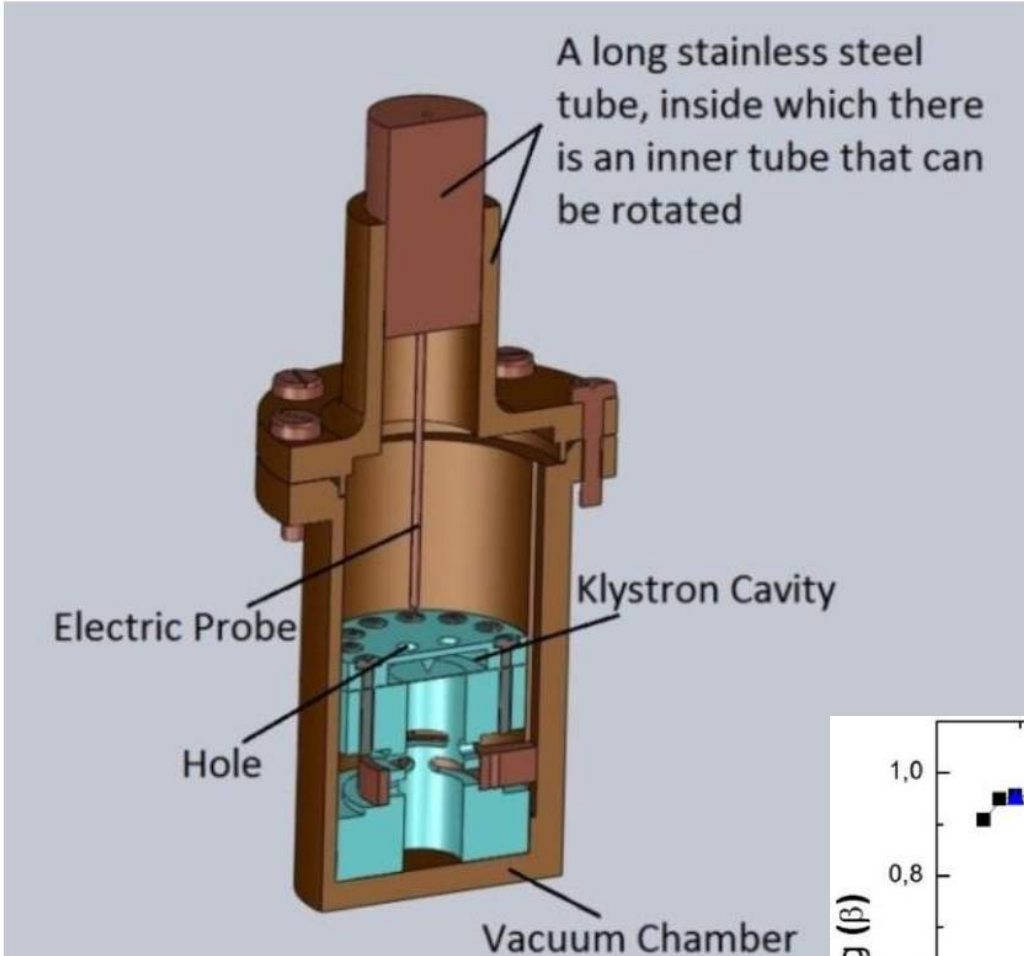
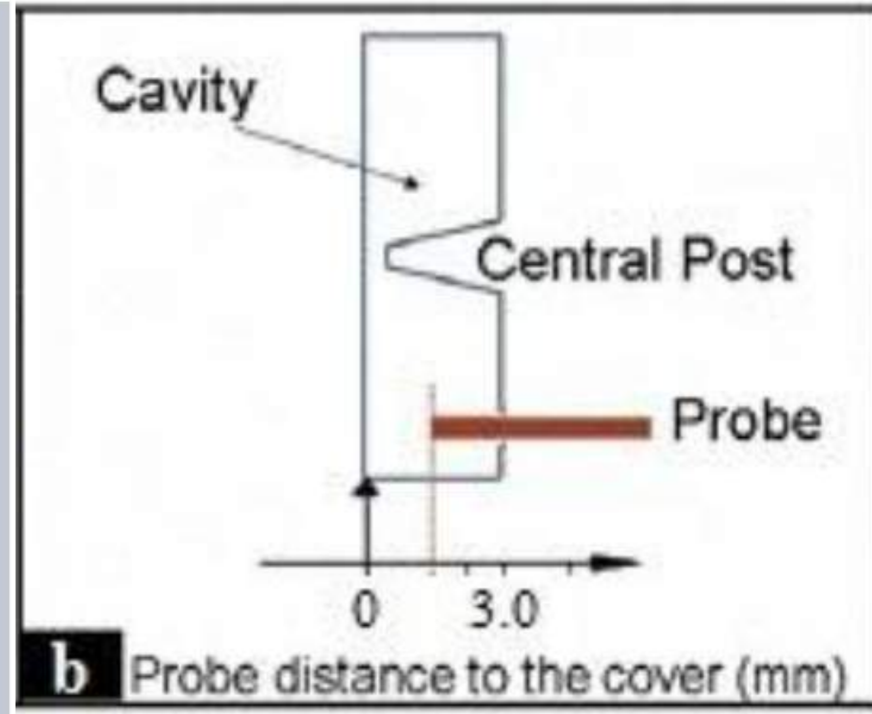
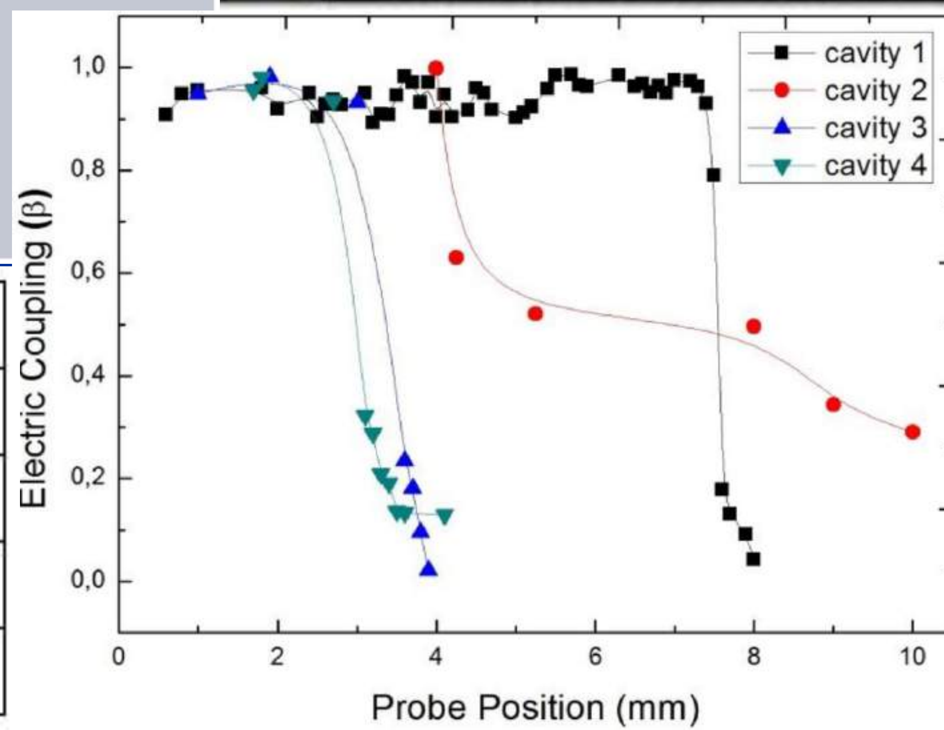




Cavity	D (mm)	P (mm)	β
3	1.5	3.9	0.02
4	2.5	4.1	0.13
1	3.0	8.0	0.04
2	3.5	10.0	0.29



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

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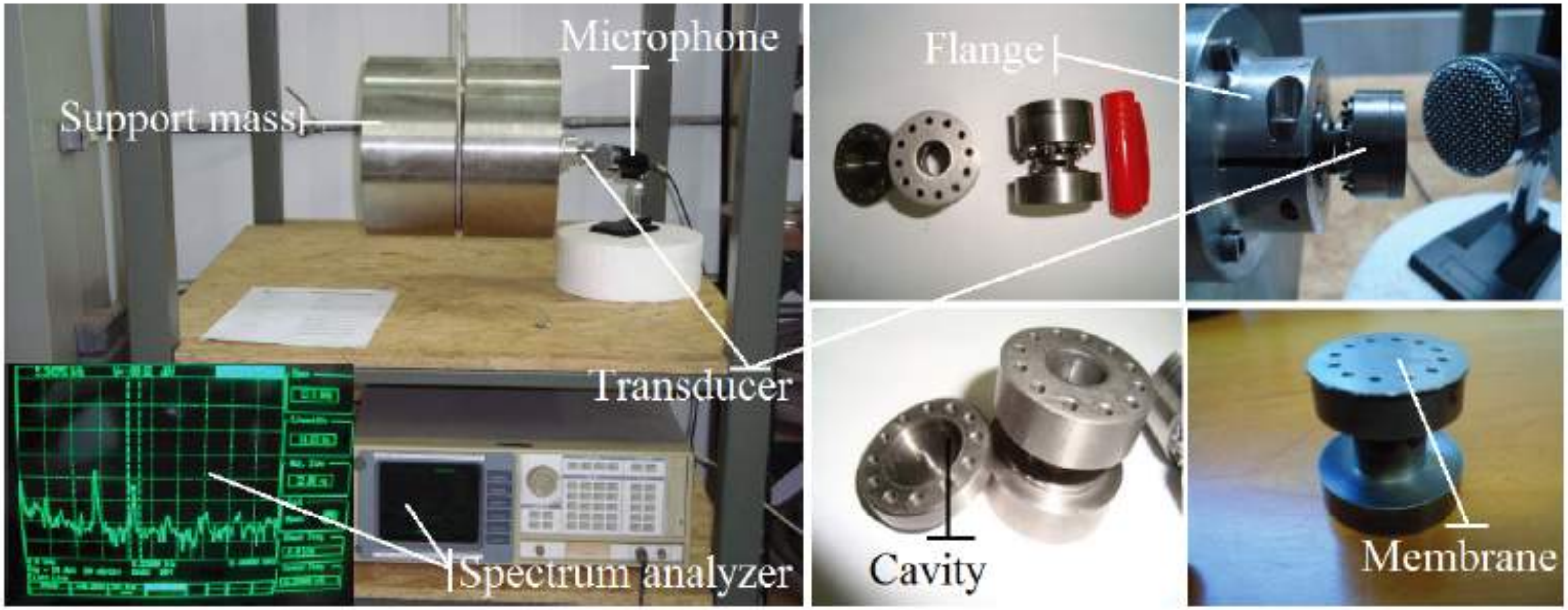


Figure 2. Equipment for measurements of mechanical resonance frequencies. The transducers were attached to the support mass and the normal modes were excited by striking the transducer. The vibrations were shown on a spectrum analyzer.

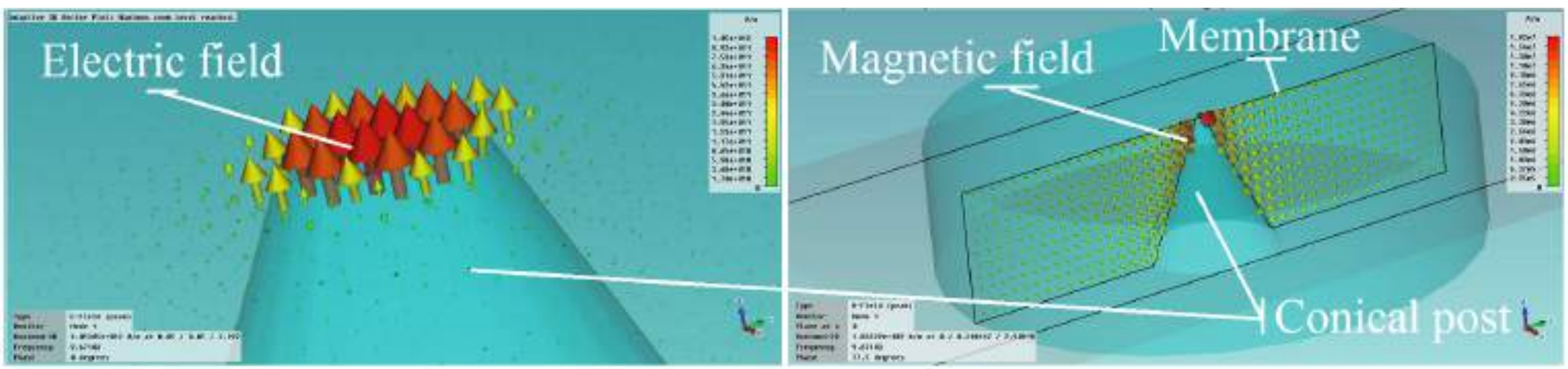


Figure 3. Electric and magnetic fields of the klystron mode for the gap of $\sim 3\,\mu$m. The electric field is much stronger at the gap region, i.e. between the top of the post and the membrane. The magnetic field shows a cylindrical symmetry around the conical post.

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**

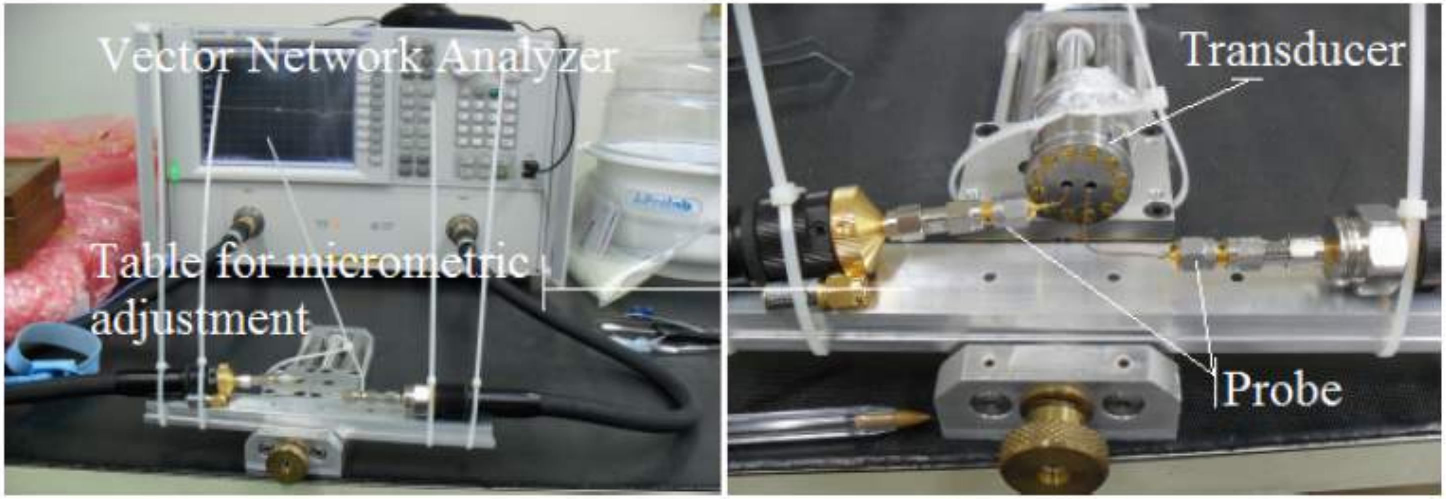


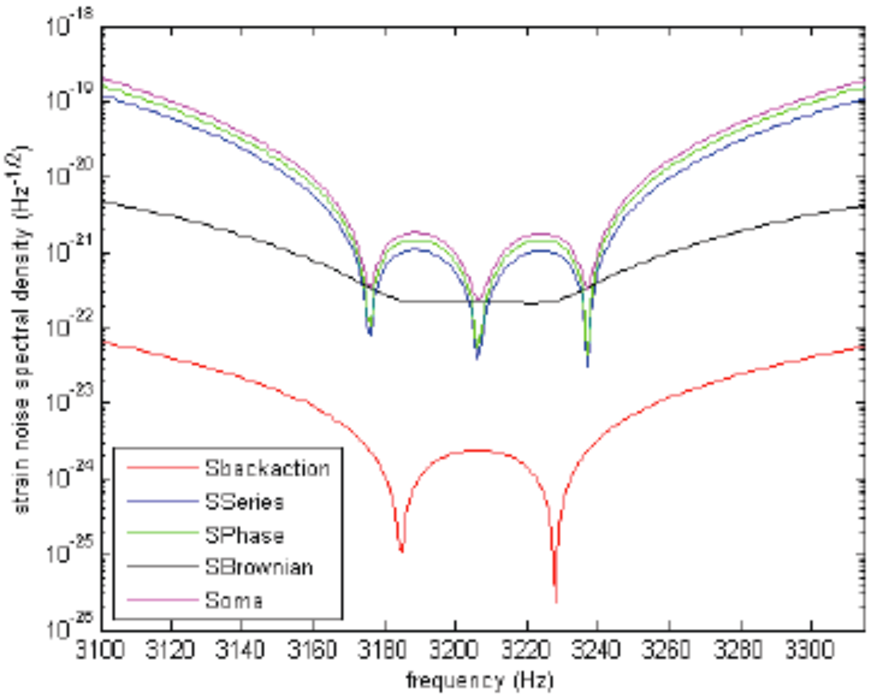
Figure 4. Frequency measurements in the vector network analyzer. The measurements were accomplished by transmission by inserting two probes into the cavity. A table for micrometric adjustment was also used in order to improve the accuracy in the probe position.

A antena no sítio de São Paulo durante as corridas em 2015

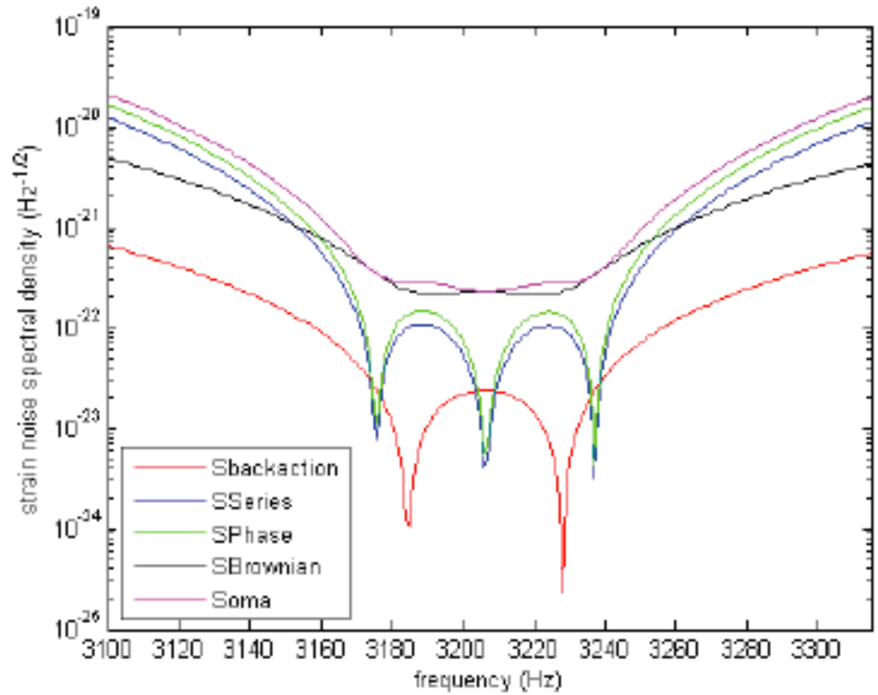
A esfera sendo removida do sítio do IFUSP em 2016

E colocada em caminhão do INPE para transporte até São José dos Campos


O Schenberg está sendo transferido para o INPE



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/μm) and $3\,\mu$m ($800\,$MHz/μm). 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.

Projeto dentro da colaboração científica LIGO (LSC)

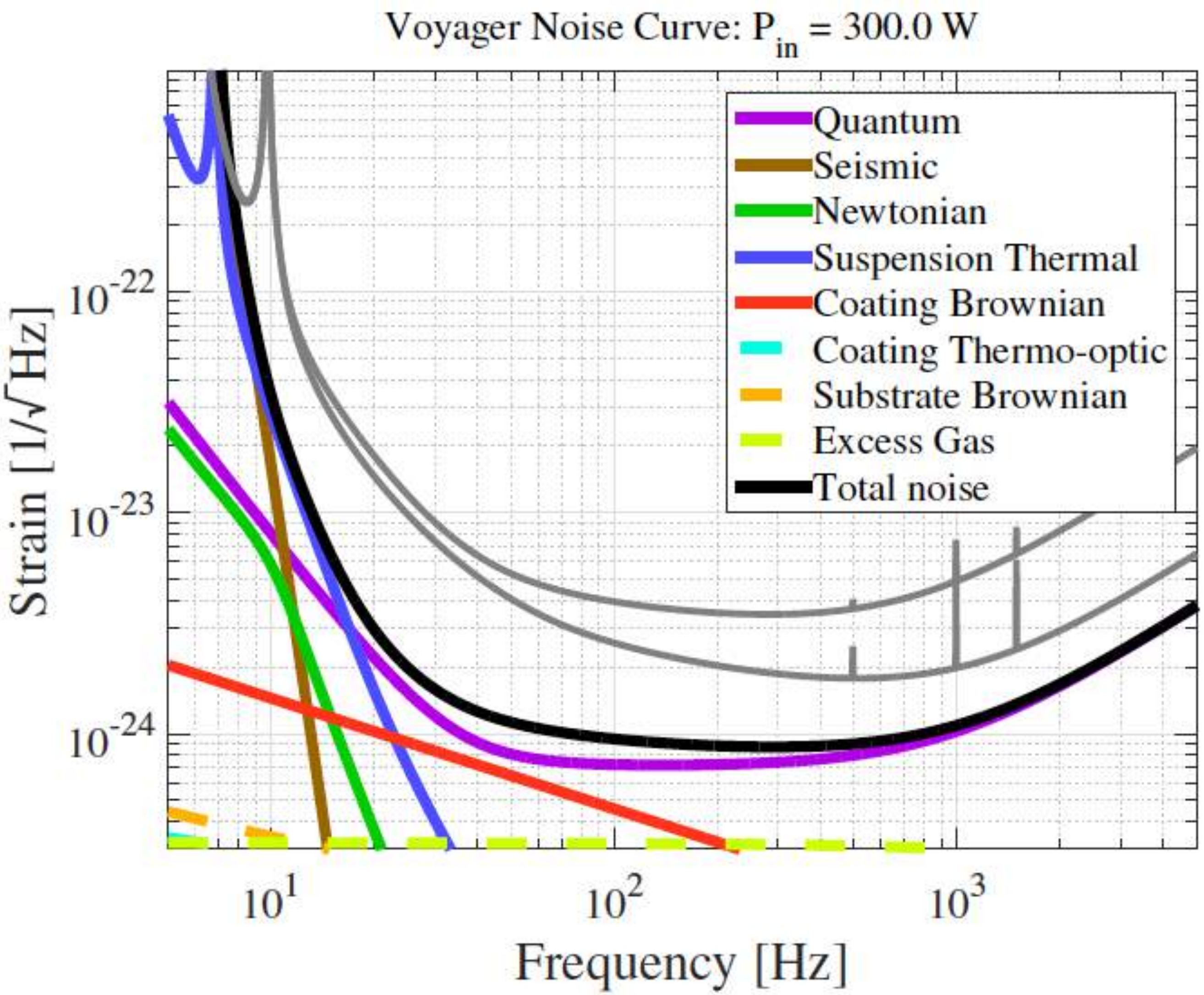
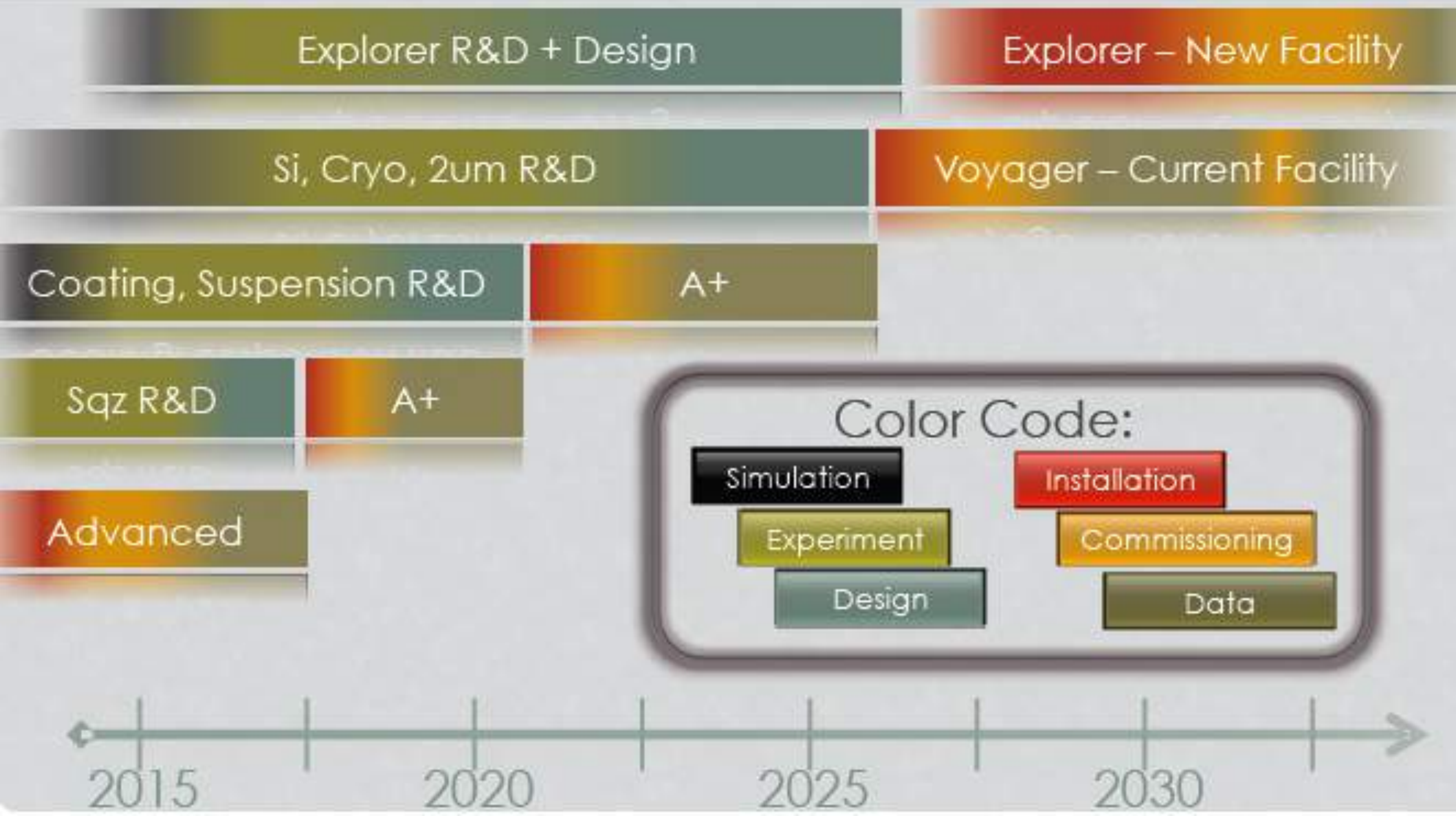
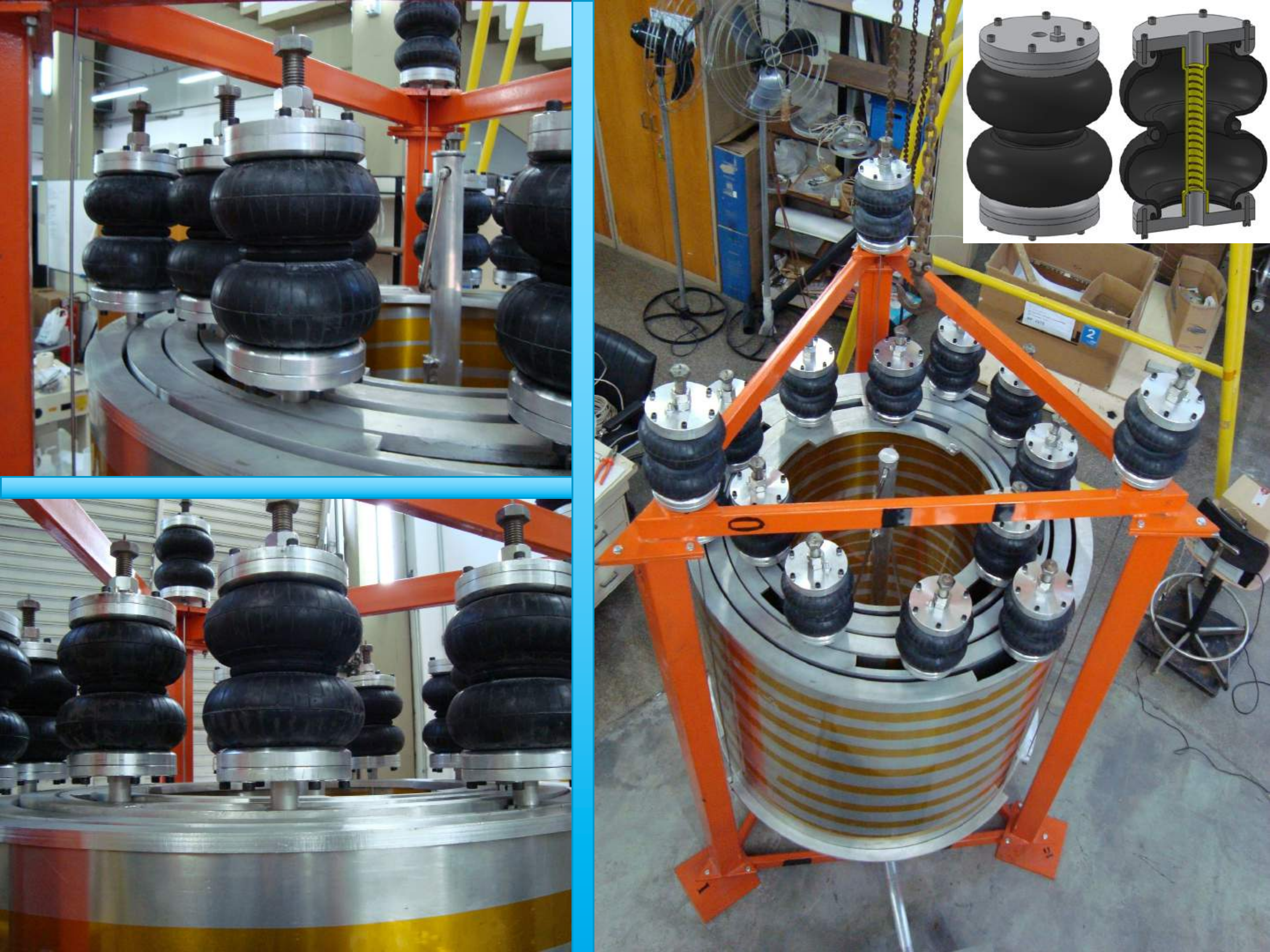
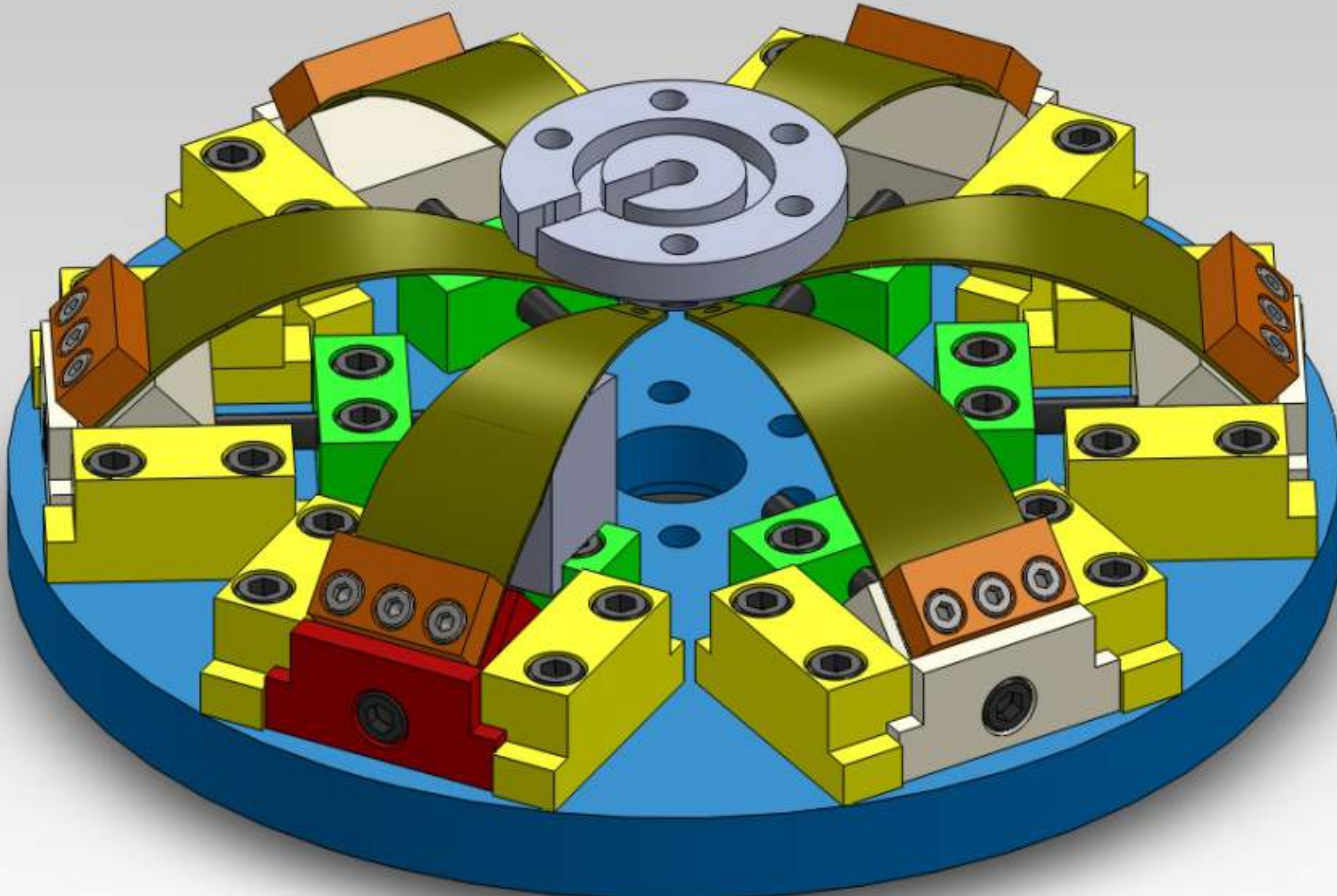


Figure 4: Conceptual noise budget for Voyager (BNS range of 1.3 Gpc). The technology assumed for these curves includes cryogenic operation at 123K, silicon optics, AlGaAs coatings, and 1550nm laser wavelength, and 8dB of frequency dependent squeezing. The Advanced LIGO and A+ sensitivities are shown in gray for reference.

LIGO Upgrade Timeline



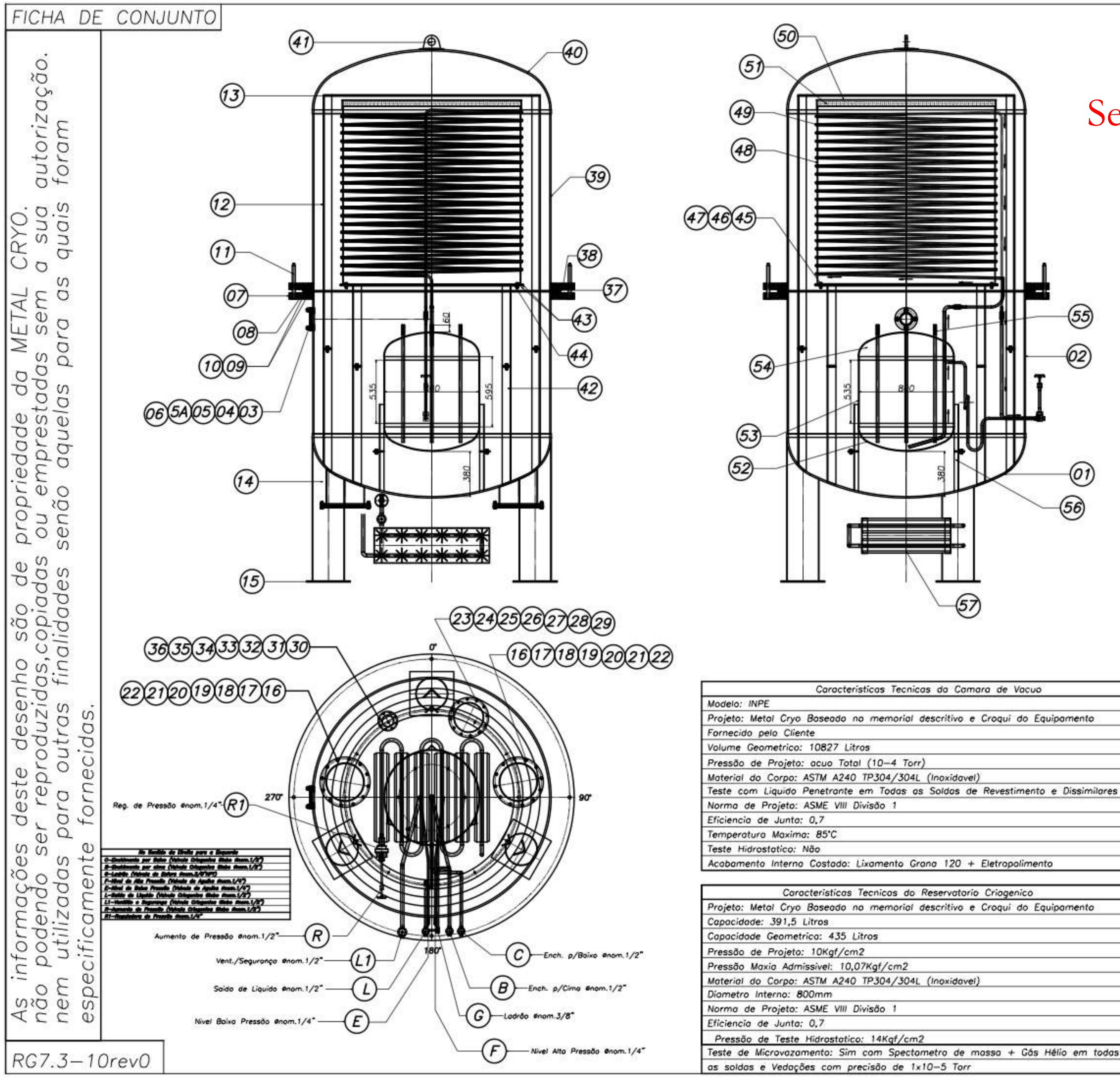




This is a schematic view of this GAS prototype.


IN
CM
8m/26ft
Lufkin

In order to do measurements in vacuum and at low temperatures, we ordered a special chamber for these purpose .



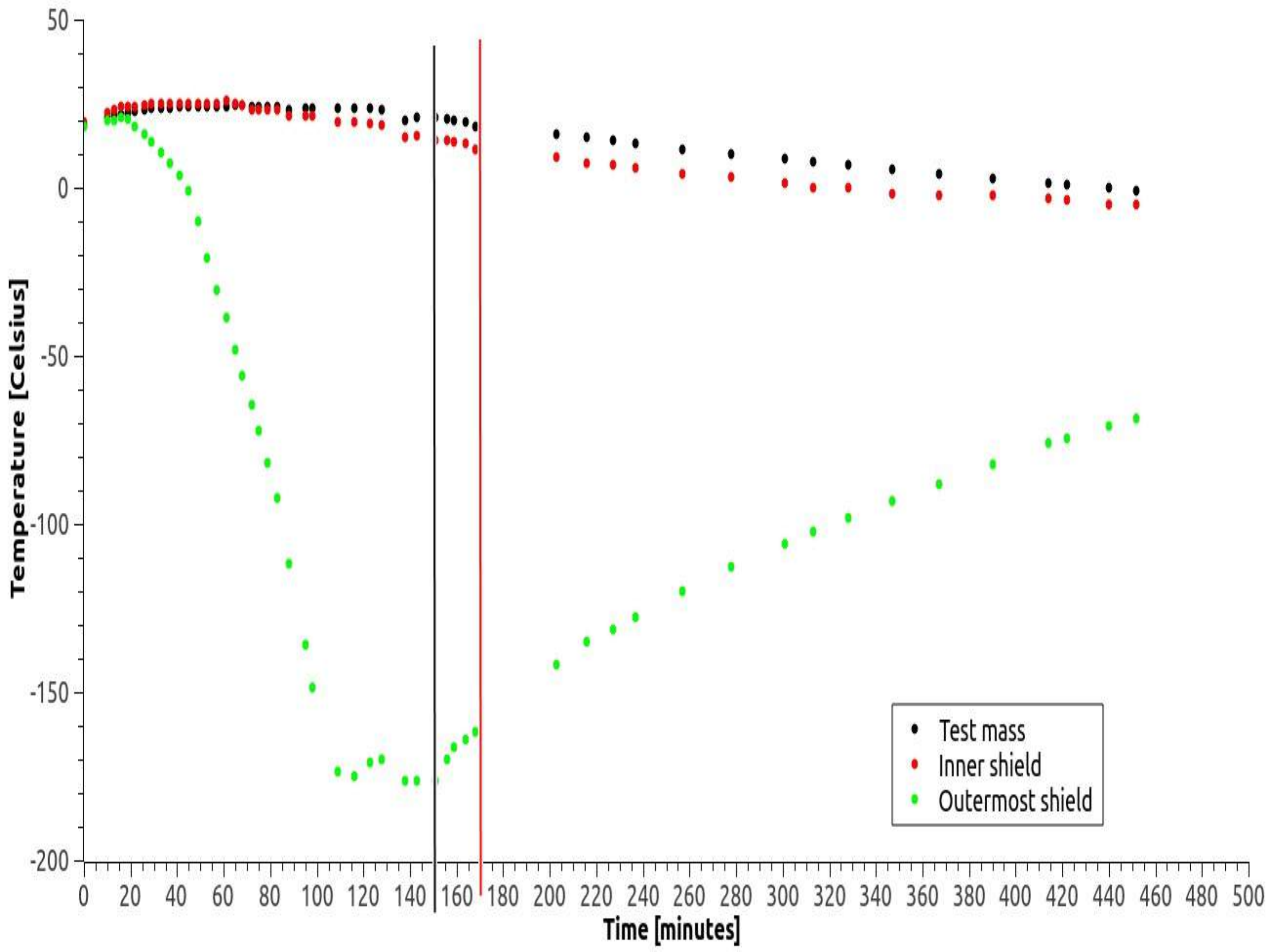
See LIGO doc T1600201

A large vacuum chamber (4.5 meters of height and 2 meters of diameter), which will be used for vacuum and low temperature tests of the MNP system and test of other alternative systems for cooling LIGO Voyager mirrors. A blue print of this chamber is shown here. The total cost of this chamber was around 200,000 US dollars, paid by the Brazilian Ministry of Science, Technology, and Innovation.


Concha inferior
Concha superior
Válvulas de controle
Serpentina de cobre


Estrutura para suspensão de cargas
Reservatório de LN2

Modelos do LIGO Voyager em escala de 1:1 podem ser testados nesta câmara



50
0
-50
-100
-150
-200
Temperature [Celsius]
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
Time [minutes]
Test mass
Inner shield
Outermost shield

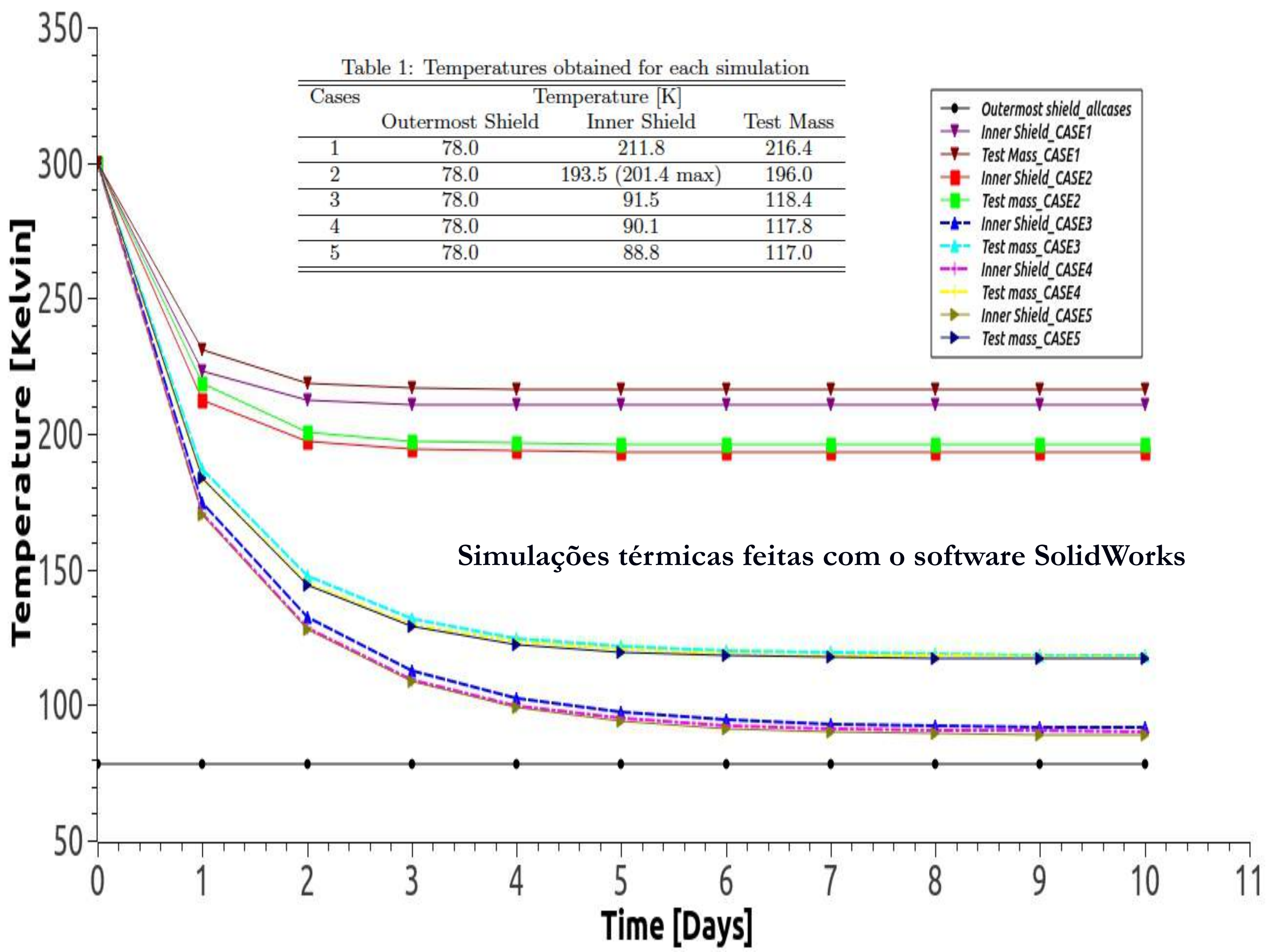


Table 1: Temperatures obtained for each simulation

Cases	Temperature [K]		
	Outermost Shield	Inner Shield	Test Mass
1	78.0	211.8	216.4
2	78.0	193.5 (201.4 max)	196.0
3	78.0	91.5	118.4
4	78.0	90.1	117.8
5	78.0	88.8	117.0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NITROGENIO
LÍQUIDO

Junte-se a nós
para
participar de novas descobertas revolucionárias na astronomia utilizando ondas gravitacionais