Doc Cont,

VIRGO

Virgo Sensitivity Curve

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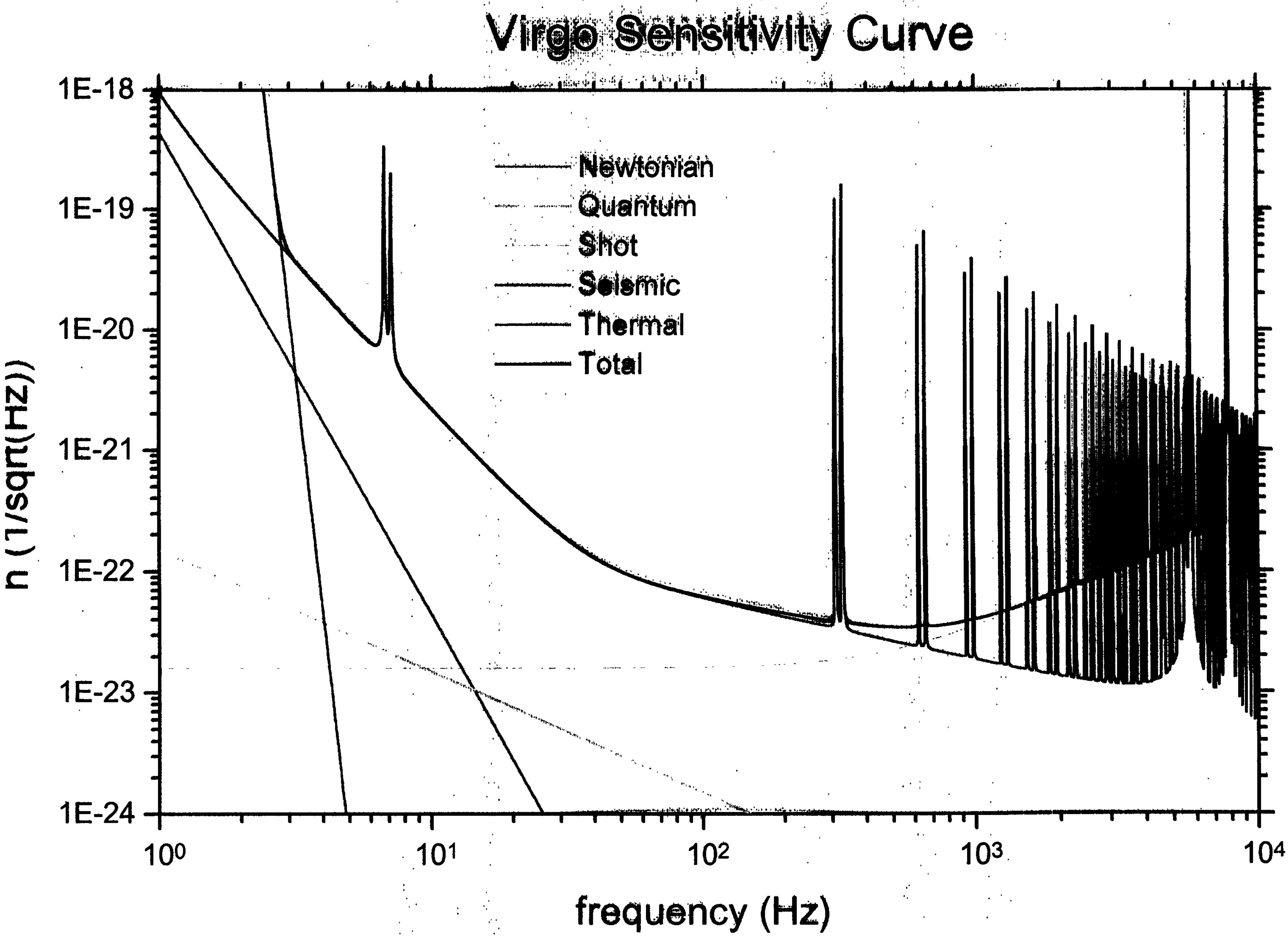
Virgo official Web site: http://www.pg.infn.it/virgo/

LIGO-G960175



Virgo Sensitivity Curve
Newtonian
Quantum
Shot
Seismic
Thermal
Total
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
h (1/sqrt(Hz))
10^0
10^1
10^2
10^3
10^4
frequency (Hz)

Shot Noise

power = 20W   fin. = 100   rec. = 50

$v0 = 500$ cut off freq.

$$hstn(f) = 1.6\cdot 10^{-23}\cdot\sqrt{1+\left(\frac{f}{v0}\right)^2} \qquad hst_{i1} := hstn(f_{i1})$$

Newtonian Noise

grav. constant $G := 6.67\cdot 10^{-11}$

Earth density $\rho e := 2000$

seismic noise (in Cascina) $PSDsys(f) := \left(\frac{10^{-7}}{f^2}\right)^2$

Plane wave param. $Dd := 200$

sound velocity $Vs = 5000$

$$DxNt(f) = \sqrt{2\cdot 12\cdot 7.48\cdot G^2\cdot \rho e^2\cdot\frac{PSDsys(f)}{(2\cdot\pi\cdot f)^4}}\cdot\sqrt{2} \qquad \text{by Saulson}$$

$$DxNt(f) := \sqrt{2}\cdot\sqrt{2}\cdot G\cdot\frac{\rho e\cdot\sqrt{PSDsys(f)}}{2\cdot\pi\cdot f\cdot Vs}\cdot Dd\cdot e^{-\left(\frac{2\cdot\pi\cdot f\cdot Dd}{Vs}\right)} \qquad \text{by Geppo}$$

$$hNt(f) := \sqrt{2}\cdot\frac{2.7\cdot G\cdot\rho e}{(2\cdot\pi\cdot f)^2}\cdot\frac{\sqrt{PSDsys(f)}}{3000} \qquad \text{by Thorne } (\Delta L)$$

$$hN_{i1} := hNt(f_{i1}) + 10^{-100}\cdot 0 \qquad hNt(4) = 1.680017\cdot 10^{-21}$$

Seismic Noise (through the superattenuator)

$$f0 = 0.759 \qquad Dsnt(f) := \sqrt{PSDsys(f)}\cdot\left(\frac{f0}{f}\right)^{18}\cdot\frac{2}{3000} \qquad \left(\frac{0.759}{4}\right)^{18} = 1.016886\cdot 10^{-13}$$

$$hS_{i1} := Dsnt(f_{i1}) \qquad Dsnt(4) = 4.237024\cdot 10^{-25}$$

Quantum limit

$$Qsnt(f) := 1.5\cdot\frac{10^{-22}}{f} \qquad hQ_{i1} = Qsnt(f_{i1})$$

Virgo Sensitivity Curve

General constants	Temperature	$T = 300$
	Boltzman constant	$kb = 1.380658\cdot10^{-23}$
	grav. acc.	$g = 9.8$

material properties

C85 steel (wires):	densità acciaio	$\rho w = 7.9\cdot10^{3}$
	cal. spec. acciaio (J/(K Kg))	$cstg = 502$
	cal.spec.per unit.vol.(J/(K m3))	$cst = cstg\cdot\rho w$
	cond. therm. acciaio (W/(m K))	$kthst = 16.3$
	coef. dil. therm. acciaio	$\alpha st = 17\cdot10^{-6}$
	yeld strength (Pa)	$BB = 2.6\cdot10^{9}$
	Young modulus (Pa)	$E = 2.1\cdot10^{11}$
	ϕ loss angle	$\phi s = 1\cdot10^{-3}$
fused quartz (mirror):	densità quarzo	$\rho m = 2.2\cdot10^{3}$
	ϕ "misurato ad Orsay"	$\phi q = 1\cdot10^{-6}$

Geometrical parameters

mirrors:

near mirror (c): mirror height $hc := .10$ $\quad lc = \frac{hc}{2}$

mirror radius $Rc = .175$

half wires separation $b1c = 0.025$

$Bc(b) := \sqrt{b^2 + Rc^2}$ $\quad Bc(b1c) = 0.176777$

mirror mass $mc := \pi\cdot Rc^2\cdot hc\cdot\rho m$ $\quad mc = 21.166481$

mirror momentum of inertia $Ic := mc\cdot\left(\frac{hc^2}{12} + \frac{Rc^2}{4}\right)$ $\quad Ic = 0.179695$

far mirror (f): mirror height $hf := .20$ $\quad lf = \frac{hf}{2}$

mirror radius $Rf = .175$

half wires separation $b1f = 0.025$

$Bf(b) := \sqrt{b^2 + Rf^2}$ $\quad Bf(b1f) = 0.176777$

mirror mass $mf := \pi\cdot Rf^2\cdot hf\cdot\rho m$ $\quad mf = 42.332961$

mirror momentum of inertia $If := mf\cdot\left(\frac{hf^2}{12} + \frac{Rf^2}{4}\right)$ $\quad If = 0.465222$

wires: length $L = 0.7$

to determine the radius we assume a safety factor of $kk = .65$

$rc = \sqrt{\frac{mc \cdot g}{4 \cdot \pi \cdot kk \cdot BB}}$ $rc = 9.883006 \cdot 10^{-5}$ $2 \cdot rc \cdot 10^6 = 197.660129$ we assume $rc = 100 \cdot 10^{-6}$

$rf = \sqrt{\frac{mf \cdot g}{4 \cdot \pi \cdot kk \cdot BB}}$ $rf = 1.397668 \cdot 10^{-4}$ $2 \cdot rf \cdot 10^6 = 279.533635$ we assume $rf = 150 \cdot 10^{-6}$

moment of inertia of the wire cross section $I2c = rc^4 \cdot \frac{\pi}{4}$ $I2f = rf^4 \cdot \frac{\pi}{4}$

------------------------------ Thermal Noise ------------------------------

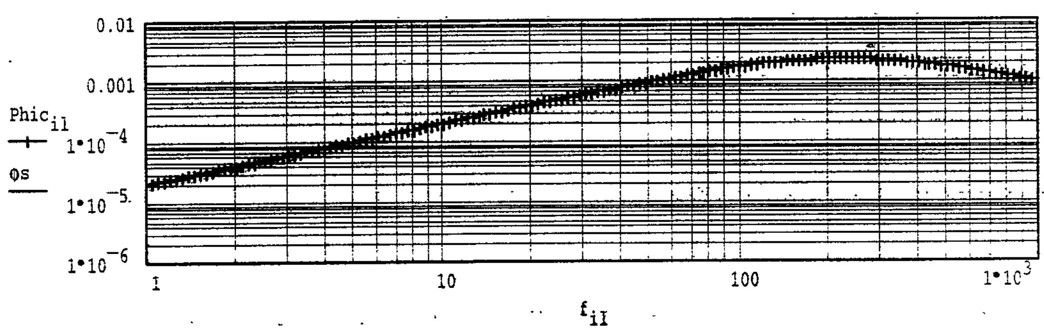
Thermoelastic damping in steel wires ----- near mirror--------------

$\Delta := \frac{E \cdot \alpha st^2 \cdot T}{cst}$ $\tau := \frac{cst \cdot (2 \cdot rc)^2}{2 \cdot \pi \cdot 2.16 \cdot kthst}$ $\frac{1}{2 \cdot \pi \cdot \tau} = 221.947652$ $\phi thc(w) := \frac{\Delta \cdot w \cdot \tau}{1 + w^2 \cdot \tau^2}$ $\Delta = 0.004591$

$\phi thc(2 \cdot \pi \cdot 1) = 2.068465 \cdot 10^{-5}$ $\phi penc(w) = \frac{1}{2 \cdot L} \cdot \sqrt{\frac{E \cdot I2c}{mc \cdot g}} \cdot \phi thc(w)$ $\phi penc(2 \cdot \pi \cdot 1) = 4.166174 \cdot 10^{-9}$

$\phi thc(2 \cdot \pi \cdot 10) = 2.064317 \cdot 10^{-4}$ $\phi penc(2 \cdot \pi \cdot 10) = 4.157818 \cdot 10^{-8}$

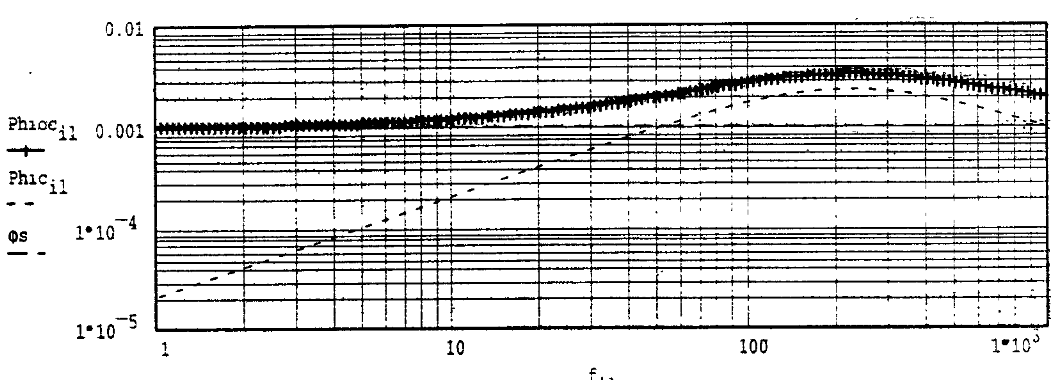
$il = 1..200$ $f_{il} = 10^{\frac{il}{50} - 1}$ $max(f) = 1 \cdot 10^3$ $f_1 = 0.104713$ $Phic_{il} = \phi thc(2 \cdot \pi \cdot f_{il})$



Si definisce un phi operativo, per i processi dissipativi nei fili, dato dalla somma del phi costante + phi termoelastico

$\phi wc(w) := \phi s + \phi thc(w)$

$Phioc_{il} = \phi wc(2 \cdot \pi \cdot f_{il})$



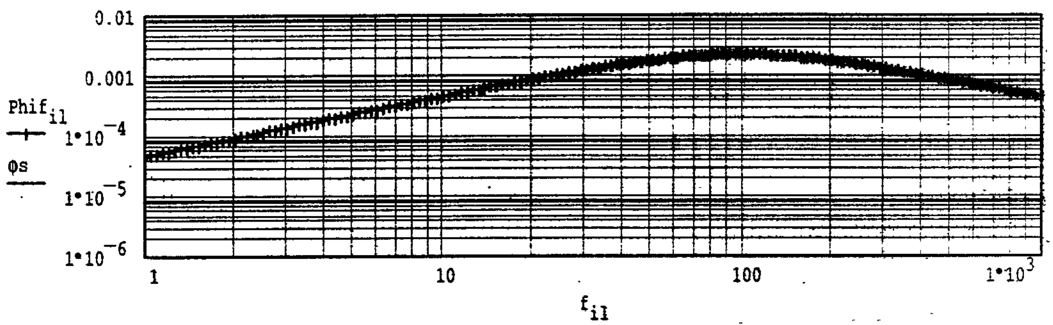
Thermoelastic damping in steel wires ----- far mirror--------------

$\Delta := \frac{E\cdot \alpha st^{2}\cdot T}{cst}$ $\quad \tau := \frac{cst\cdot(2\cdot rf)^{2}}{2\cdot\pi\cdot 2.16\cdot kthst}$ $\quad \frac{1}{2\cdot\pi\cdot\tau} = 98.643401$ $\quad \phi thf(w) := \frac{\Delta\cdot w\cdot\tau}{1+w^{2}\cdot\tau^{2}}$ $\quad \Delta = 0.004591$

$\phi thf(2\cdot\pi\cdot 1) = 4.653663\cdot 10^{-5}$ $\quad \phi penf(w) := \frac{1}{2\cdot L}\cdot\sqrt{\frac{E\cdot I2f}{mf\cdot g}}\cdot\phi thf(w)$ $\quad \phi penf(2\cdot\pi\cdot 1) = 1.491254\cdot 10^{-8}$

$\phi thf(2\cdot\pi\cdot 10) = 4.606797\cdot 10^{-4}$ $\quad \phi penf(2\cdot\pi\cdot 10) = 1.476236\cdot 10^{-7}$

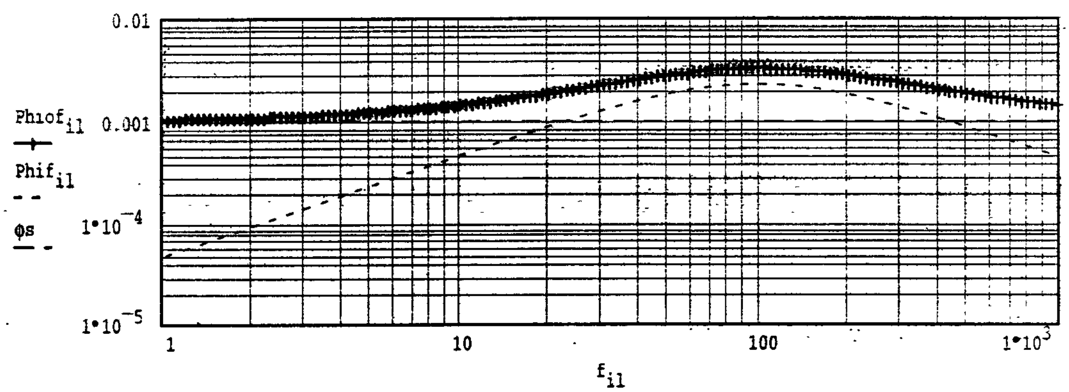
$Phif_{il} := \phi thf(2\cdot\pi\cdot f_{il})$

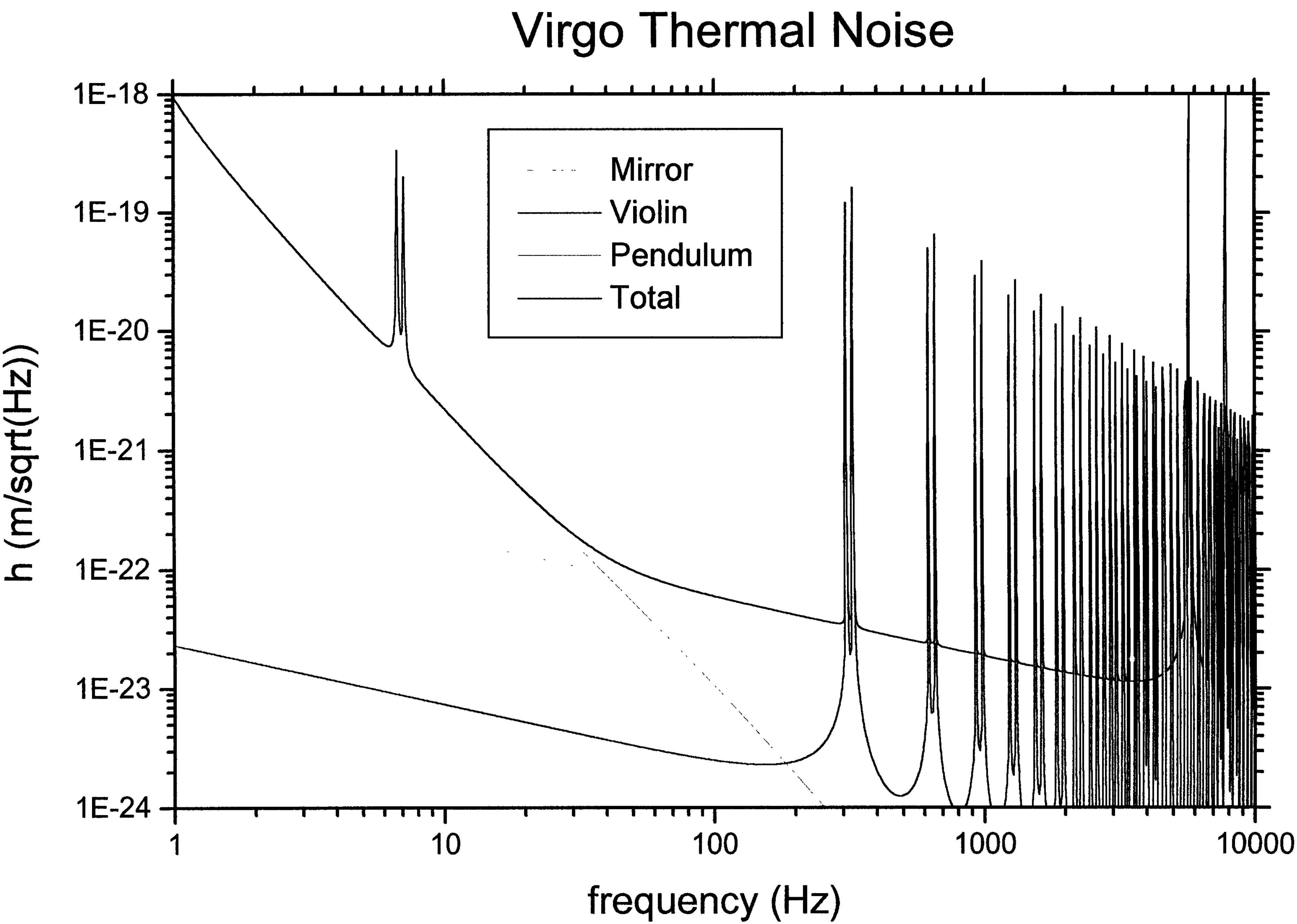


Si definisce un phi operativo, per i processi dissipativi nei fili, dato dalla somma del phi costante + phi termoelastico

$$\phi wf(w) := \phi s + \phi thf(w)$$

$Phiof_{il} := \phi wf(2\cdot\pi\cdot f_{il})$




Virgo Thermal Noise
Mirror
Violin
Pendulum
Total
h (m/sqrt(Hz))
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
1
10
100
1000
10000
frequency (Hz)

On Going Thermal Noise Research

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VIRGO Project

Overview

- **VIRGO** deliverables
  - clamps and wires
  - reference solution
- thermal noise predictions
- wire and clamp research
- creep research (preliminary)
- full scale prototype Q measurements
- long term R&D

VIRGO deliverables

- Suspension
  - (7 m inverted pendulum with milliHertz horizontal resonance)
  - 7 stage pendulum (superattenuator)
- last stage
  - one wire to a "marionetta"
  - two wire loops hung from marionetta
    - ◇ allows pitch of mirror to be controlled by marionetta
  - wire clamped on marionetta
  - wires simply looped around mirrors
- Perugia Group must deliver clamps and wires for all last stage components by Sept. 96 (March 97?)

VIRGO Reference solution

- VIRGO arm length– 3 km
- Pendulum length 700mm or pend. freq=0.6Hz
- wire loop separation 50 mm
- mirror made of Herasil with unpolished sides (ground finish)

- near mirror
  - thickness=100 mm
  - diameter=350 mm
  - mass=21.2 kg
  - C85 harmonic steel wire with diameter $=200\mu m$ (safety factor of .65 with breaking load=$300 kg/mm^2$ (3 GigaPascals))
  - yaw mode frequency=1.2 Hz
  - pitch mode frequency=1.8 Hz
  - vertical mode frequency=6.7 Hz
- far mirror
  - thickness=200 mm
  - diameter=350 mm
  - mass=42.4 kg
  - C85 harmonic steel wire with diameter $=300\mu m$
  - yaw mode frequency=1.0 Hz
  - pitch mode frequency=1.7 Hz
  - vertical mode frequency=6.9 Hz
- clamps
  - aluminum with tool steel inserts
  - (put grooves 130μ deep on only one inner tool steel face)
  - use 2 M6 screws tightened to 14 Nm torque to clamp two pieces on wire

wire and clamp research

- small pendulum in vacuum
  - loaded with only a few hundred grams
  - test pendulum Q
  - find pendulum Q agrees with material ϕ if wire is clamped with sufficient pressure
  - will now start to look at violin modes also (preliminary results seem to agree with wire loss and thermoelastic effect)
- traditional ineternal friction tests (inverted pendulum, torsional pendulum, temperature dependence, annealing effects) also done at
  - University of Camerino(Italy)
  - Technical University of Gdansk (Poland)
- looked at some monolithic designs
  - electroerosion of strip–promising, but geometry not good
  - centreless grinding of wire–damges both yield strength and ϕ
- tests of yield strength and ageing effects in wire

creep research

- baking at 150° for 1 week
- long term sinking of mirror
- creep noise coupling into gravity wave signal
- some preliminary tests
- development of sensitive shadow meter
- eventual search for creep events

Full Scale Prototype Q Measurements

low recoil loss structure

- Q limited by recoil losses

$$\frac{E_1}{Q_1} = \frac{E_2}{Q_2}$$
$$k_1\phi_1 = k_2\phi_2$$
$$Q = \frac{Mg}{kl\phi}$$

  - predicted k (using finite element analysis)$= 2 \times 10^8 N/m$
  - predicted $\phi =< 1°$????
  - Q limited to (M=20 kg) $> 4 \times 10^7$?????

- structure
  - Steel plates welded in an "A" frame type stucture
  - Structure bolted directly to vacuum tank
  - Vacuum tank clamped to concrete block
  - 1.5m X 1.5m X 0.5m
  - 6 bolts embedded in block

- Dynamic characterization test using a 65 kg mass hung as a pendulum
  - Measure both phase and magnitude of transfer function
  - measure at pendulum frequency ($\approx 0.6 Hz$)
  - use DC coupled accelerometer to measure acceleration (force) of mass
  - shadow meter measures displacement at the top of the structure
  - important that shadow meter reference is stationary
  - must calibrate both magnitude and phase of accelerometer

- must calibrate shadow meter
  (phase is negligibly small since shadow meter is large bandwidth device)

- do a DC test to measure elastic constant of structure
  - use a string, pulley and some weight to exert a force on the top of the structure
  - measure displacement using shadow meter
  - serves as independent test of elastic constant

- structure itself
  - measured relative to base of vacuum system
  - spring constant $k = 1.13 \pm 0.03 \times 10^8 N/m$

- recoil of total system
  - measured relative to wall of building
  - spring constant $k = 3.5 \pm 0.1 \times 10^7 N/m$
  - phase $0.94 \pm 0.08°$
  - cement block moves
  - depends upon orientation of pendulum motion
  - depends upon tightness of clamping tank to block

- Recoil losses of structure set an upper limit to the Q measurement (for a 20 kg mass) of $Q = 7.6 \pm 0.7 \times 10^6$ (best predicted $Q = \frac{1}{2} \times 5 \times 10^6$)

- system will be moved in the near future (by Sept. 96)
  - new lab space available
  - installation of overhead crane to meet EC regulations
  - bigger concrete block and more bolts
  - test the structure with a mechanical shaker for a better characterization (better phase measurement over a broader frequency)

Pendulum (and violin mode) Q measurements

- Q depends upon
  - internal losses in wire
  - clamping (both top and bottom)
  - recoil losses in structure
  - vacuum
- a Q of 10^6 and a pendulum frequency of 0.60 Hz gives
  - relaxation time of 5.3×10^5 seconds (147 hours or 6 days)
  - seismic noise of $10^{-6} m/\sqrt{Hz}$ gives an $x_{r.m.s.} = 0.8\ mm$
  - linewidth of resonance is $0.6 \mu Hz$
- hang mass using springs to pre–tension wires
- excite pendulum mode (and violin modes) electrostatically using positive feedback
- measure wire motion with traditional shadow meter technique (bi–cell photodiode and LED)
- place shadow meter near top of wire
  - large motions of mass can still be measured using wire as shadow
  - allows violin modes to be measured with same device
- record time series with PC
  - take amplitude and fit with exponential decay
  - also use two decaying exponentials that are close in frequency

$$A(t) = A_1 e^{-\gamma_1 t} + A_2 \sin[2\pi(f_2 - f_1)t) + \phi] e^{-\gamma_2 t}$$

- measure resonance linewidth with FFT spectrum analyser
  - fit curve with Lorentzian

Al dummy mirror

- aluminum mass with same dimensions ($350 \times 100mm$), but larger mass($\rho_{Al} = 2.7g/cm^3$ vs. $\rho_{SiO_2} = 2.2g/cm^3$ or $m_{Al} = 26.0kg$ vs. $m_{SiO_2} = 21.2kg$)
  - $Q_{pend} = \frac{1}{2} \times 5.6 \times 10^6$
  - violin mode $f_n = n \times 362\ Hz$
  - violin mode Q (at 362 Hz)$= 7.5 \times 10^5$
- reference solution set up (**no** clamps)
  - Q of pendulum extremely amplitude dependent
  - best Q (limited by seismic excitation) of 1×10^5
  - violin mode Q also amplitude dependent
  - best violin mode $Q \sim 2 \times 10^4$
- wire attached with epoxy to test mass
  - Q of pendulum less amplitude dependent
  - best Q (limited by seismic excitation) of 1×10^5
  - violin mode $Q \sim 8 \times 10^4$
- wire attached with clamps to test mass
  - Q of pendulum shows little amplitude dependence
  - best Q of $Q \sim 6 \times 10^5$
  - violin mode $Q \sim 2.2 \times 10^5$
  - Q of pendulum could be limited by eddy current damping of Al mass moving through the earth's magnetic field (Thank you Sheila for the calculation!)

Herasil test mass

- reference solution suspension
  - pendulum mode $Q \sim 10^4$
  - violin mode $Q \sim 8 \times 10^3$
  - both very highly amplitude dependent
  - **not** acceptable Q for VIRGO
- measured Herasil mirror with cylindrical AL spacers between wire and mirror surface
  - pendulum mode $Q \sim 4 \times 10^5$
  - violin mode $Q \sim 1.5 - 2 \times 10^5$
  - **tried both 5mm and 10mm diameter and did not see much difference**
- measured Herasil mirror with cylindrical SS spacers between wire and mirror surface
  - pendulum mode $Q \sim 3 \times 10^5$
  - violin mode $Q \sim 9 \times 10^4$
- measured Herasil mirror with grooved, cylindrical AL spacers between wire and mirror surface
  - grooves were narrower than wire radius
  - pendulum mode $Q \sim 4 \times 10^5$
  - violin mode $Q \sim 2.1 - 2.5 \times 10^5$
- measured Herasil mirror with clamps attached to cylindrical AL spacers between wire and mirror surface
  - pendulum mode $Q \sim 6 \times 10^5$
  - violin mode $Q \sim 2 - 4 \times 10^5$

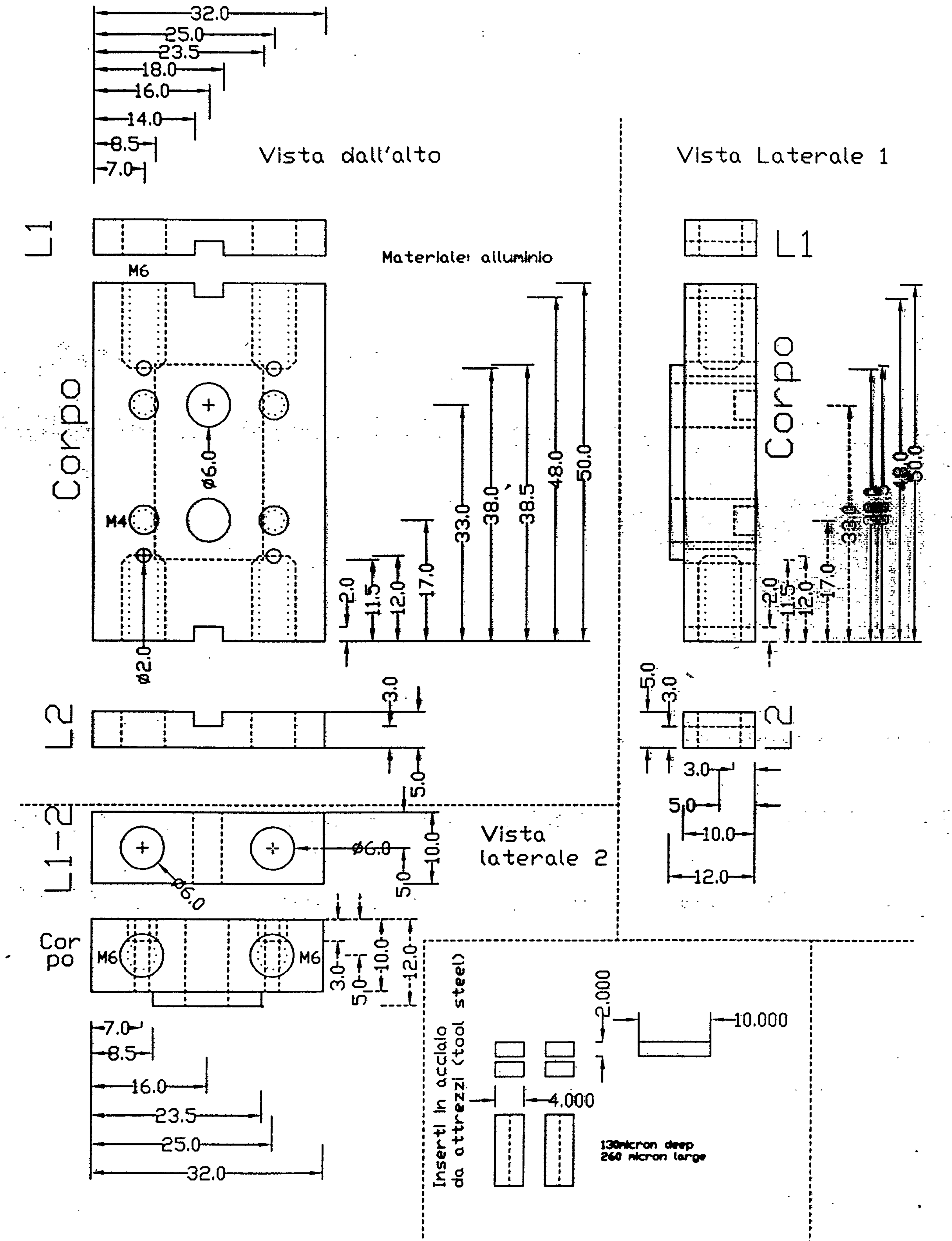
- measured dummy glass mirror with Al clamps epoxied onto mirror surface
  - pendulum mode $Q \geq 5 \times 10^5$
  - violin mode $Q \sim 2 \times 10^5$

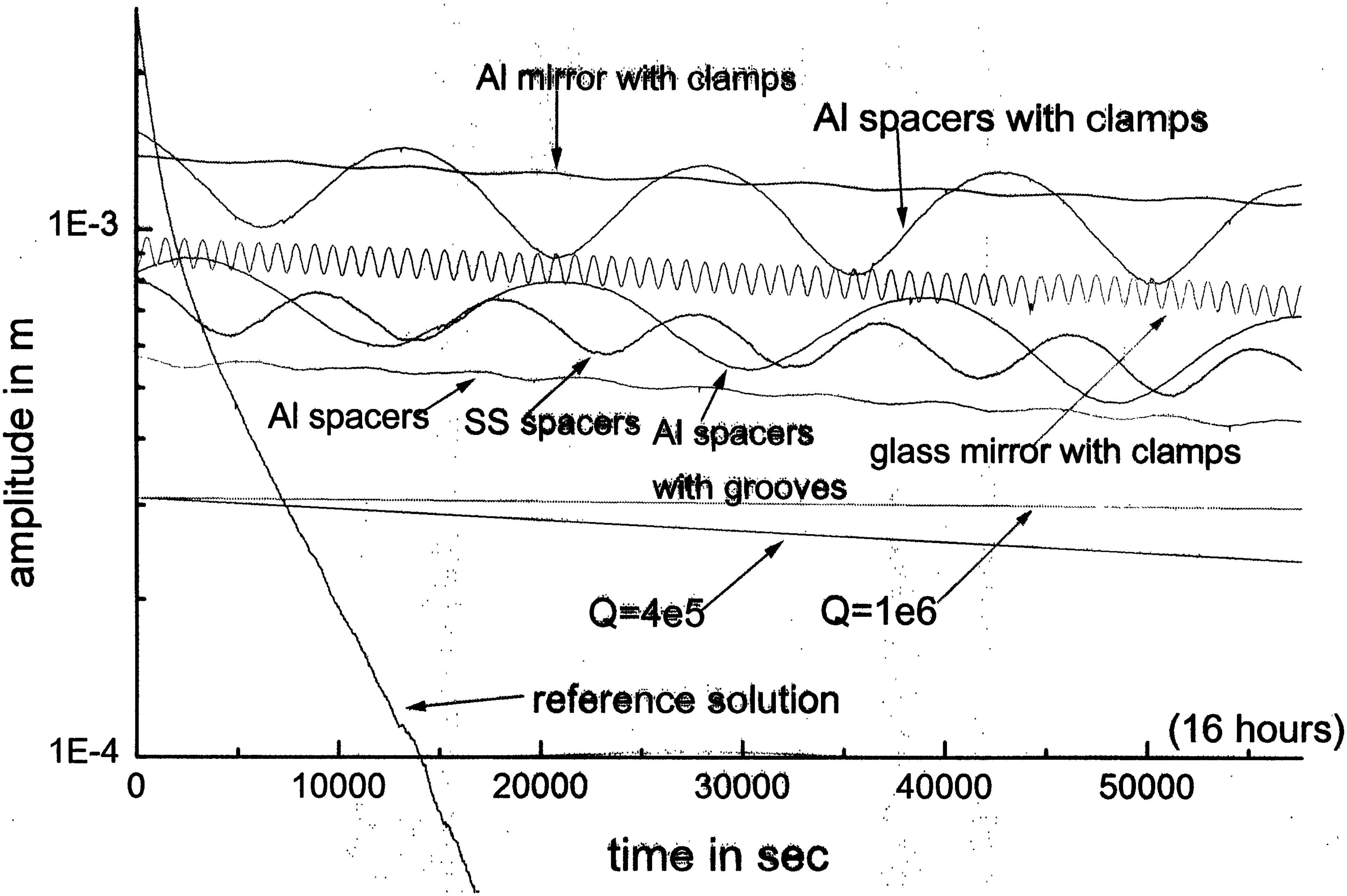
other modes (using Herasil mass)

- yaw mode
  - excite electrostatically by rotating and displacing plate
  - Ref. Solution $f = 1.16\ Hz,\ Q = 2.1 \times 10^4$ (amplitude dependent)
  - spacers with grooves $f = 1.17\ Hz,\ Q = 5.6 \times 10^5$
- pitch mode
  - excite electrostatically by displacing plate
  - Ref. Solution $f = 1.91\ Hz,\ Q = 1.3 \times 10^3$
  - spacers with grooves $f = 1.78\ Hz,\ Q = 3.1 \times 10^3$
- vertical mode
  - excite by shaking ground mechanically
  - Ref. Solution $f = 6.65\ Hz,\ Q = 1.9 \times 10^3$
  - spacers with grooves $f = 6.44\ Hz,\ Q = 1.8 \times 10^3$

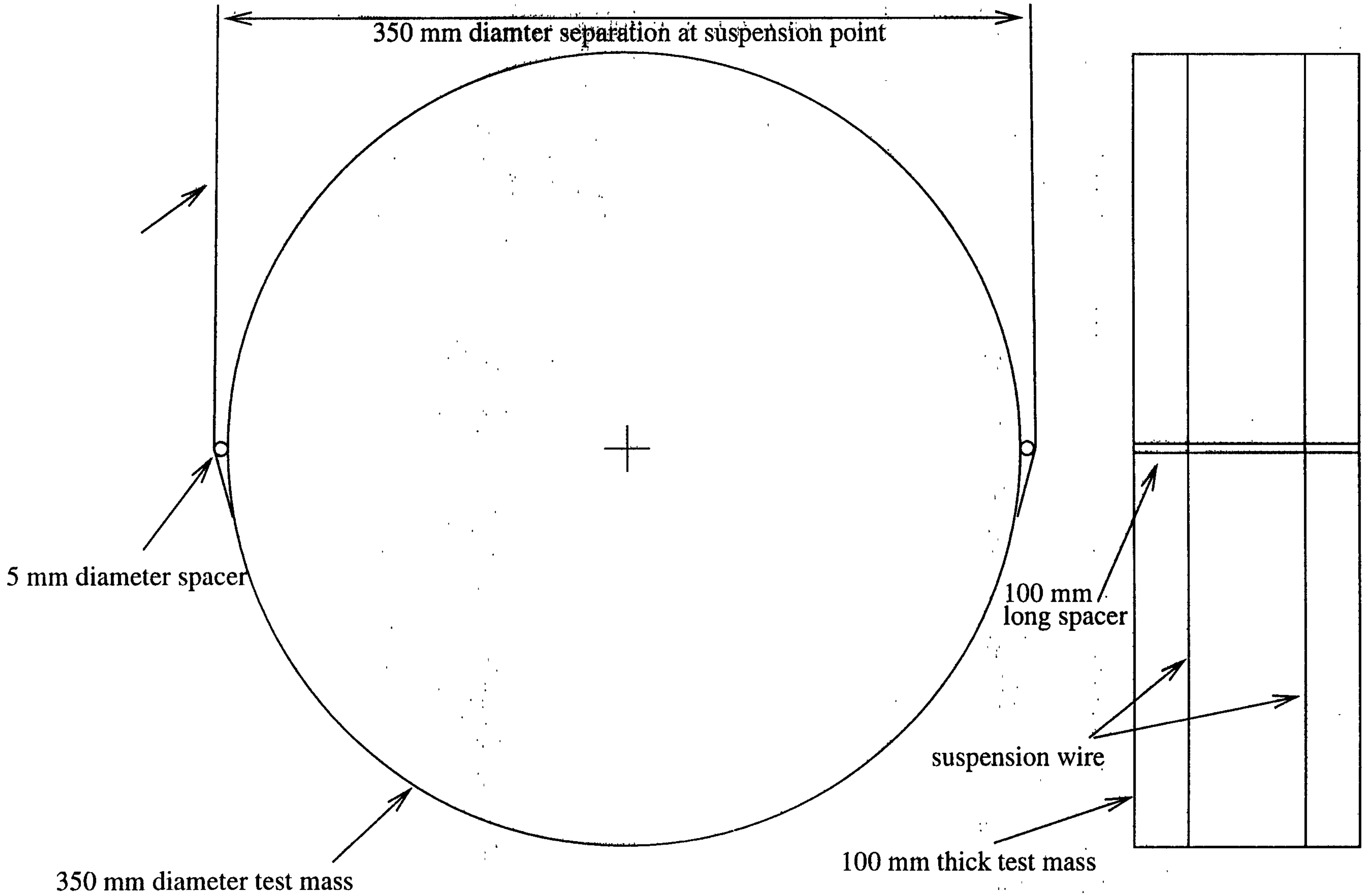
long term R&D

- new wire materials
  - search for specialty materials
  - fused quartz (small prototype had $a\phi = 5 \times 10^{-6}$)
- better clamps
  - collet type clamp
  - monolithic designs
- sapphire test masses
  - collaboration with LIGO and Univ. of Western Australia
  - sapphire to be obtained by LIGO an VIRGO
  - optics to be tested in Paris
  - suspension and Q to be tested in Australia
- cryogenics
- direct thermal noise measurement


Vista dall'alto
Vista Laterale 1
Materiale: alluminio
L1
Corpo
M6
M4
ø6.0
ø2.0
L2
L1-2
Vista laterale 2
Cor po
Inserti in acciaio da attrezzi (tool steel)
130micron deep
260 micron large
32.0
25.0
23.5
18.0
16.0
14.0
8.5
7.0
2.0
11.5
12.0
17.0
33.0
38.0
38.5
48.0
50.0
3.0
5.0
10.0
2.000
10.000
4.000



Al mirror with clamps
Al spacers with clamps
1E-3
Al spacers
SS spacers
Al spacers
with grooves
glass mirror with clamps
Q=4e5
Q=1e6
reference solution
(16 hours)
1E-4
0
10000
20000
30000
40000
50000
time in sec
amplitude in m


350 mm diamter separation at suspension point
5 mm diameter spacer
350 mm diameter test mass
100 mm
long spacer
suspension wire
100 mm thick test mass

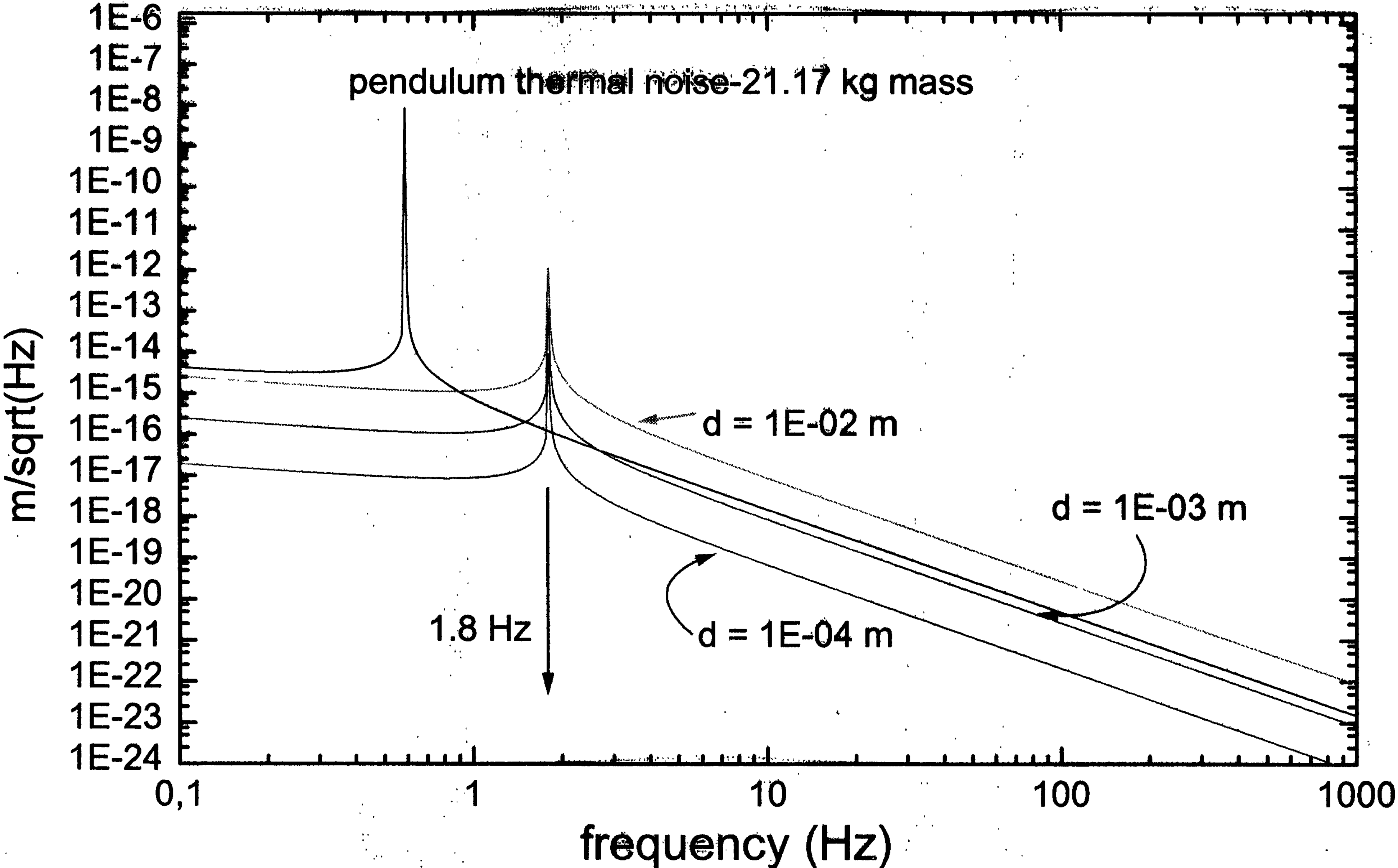

pendulum thermal noise-21.17 kg mass
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
m/sqrt(Hz)
d = 1E-02 m
d = 1E-03 m
d = 1E-04 m
1.8 Hz
0,1
1
10
100
1000
frequency (Hz)

Fig. 4