Last stage suspensions of VIRGO Mirrors

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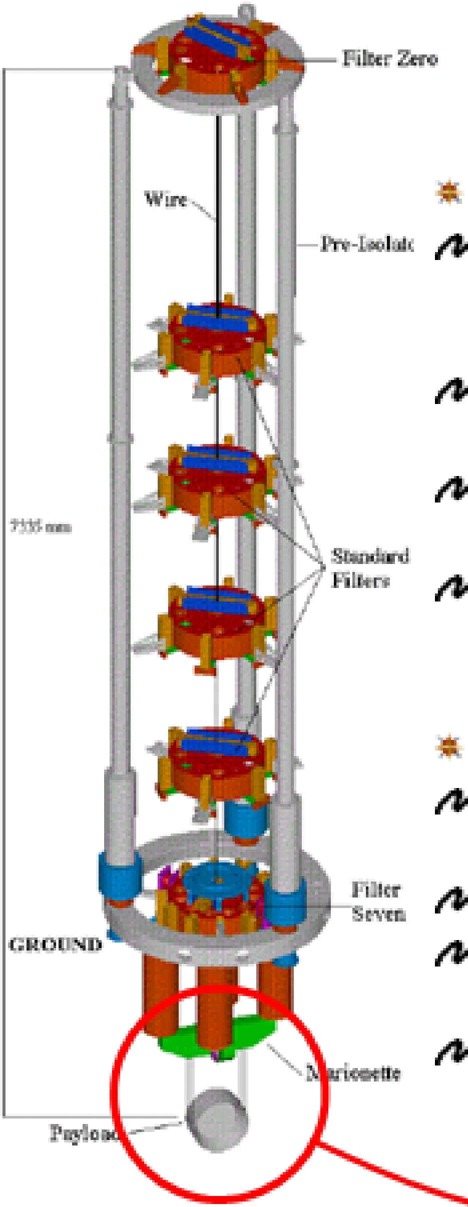
Summary

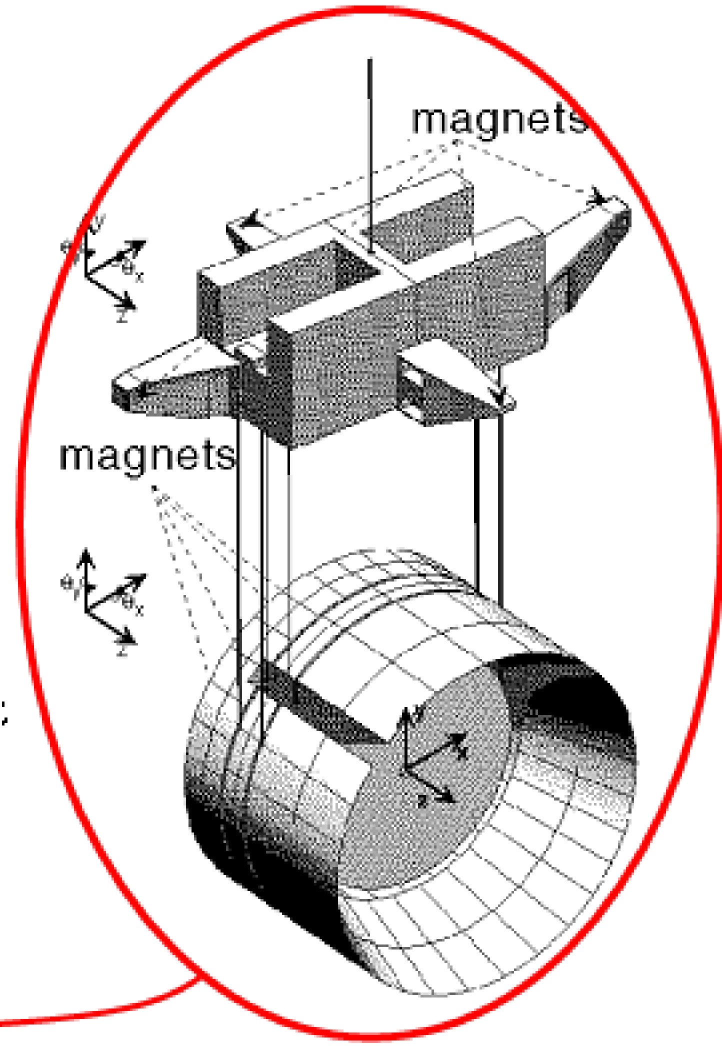
- The last stage suspension: its requirements and how it works;
- The last stage in the Virgo Central ITF;
- Studied problems during the CITF commissioning and improvements:
  - *Mechanical characteristics of the system mirror+holder;*
  - Non linear effects;
- Study of the West Input Payload modes in the E4 data of the CITF;
- Conclusions

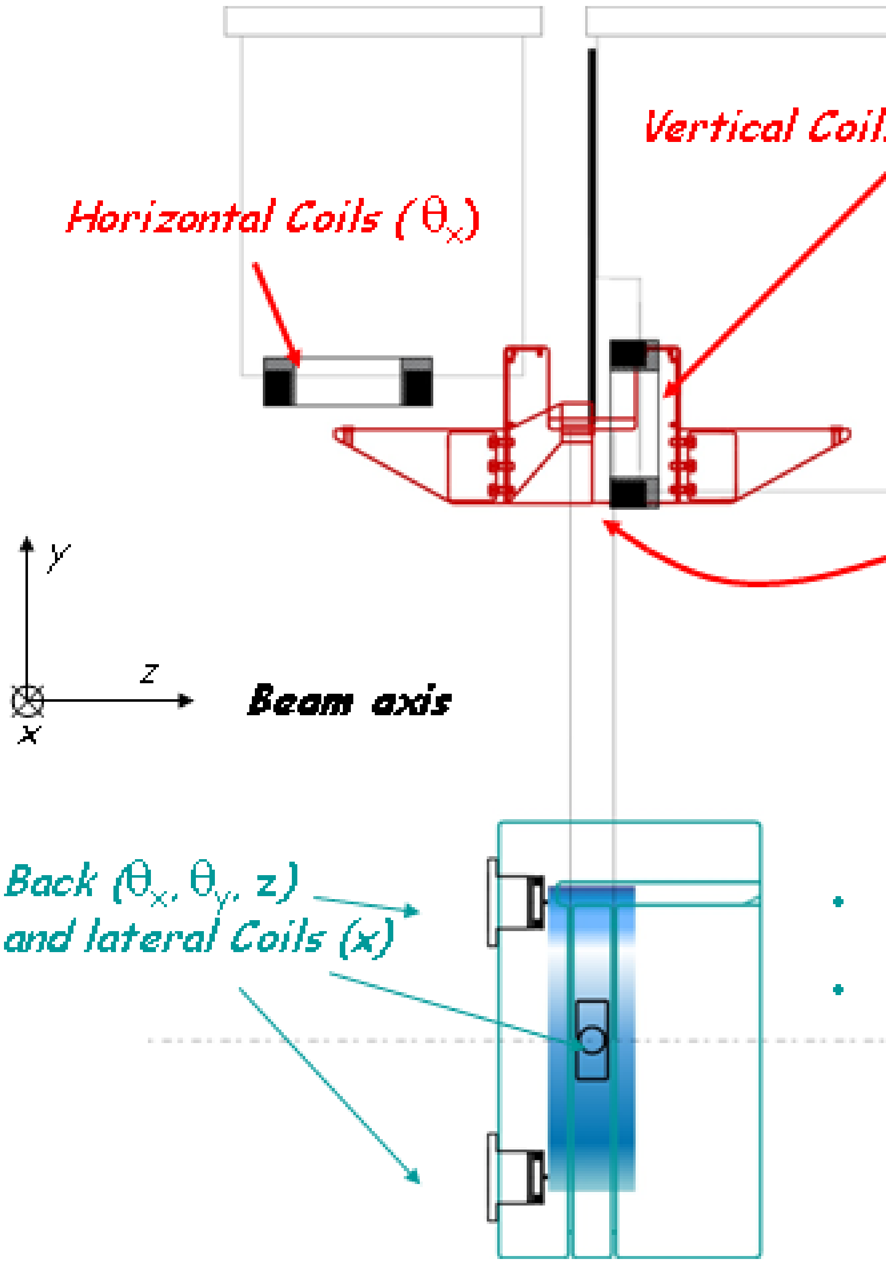


The Last Stage Suspension

- **How it works**
  - it permits to control the mirror longitudinal and angular position in the low frequency range;
  - it damps the low frequency pendulum oscillations;
  - it keeps the interferometer on the working point;
  - it provides further 40 dB of seismic attenuation;

- **Requirements:**
  - Ultra High Vacuum and Clean Room compatibility;
  - Internal frequencies as high as possible;
  - Geometry compatible with beams sizes and position measurements;
  - Geometry useful for protection of the mirrors from contamination;





The Marionetta...

- ...controls the tilts θ_x, θ_y, and the translations along z.

  e.m. actuators are used with a force coefficient of 25 mN/A

- ...can statically tilt the mirror to align the interferometer (10 mrad range, 1 µrad resolution).

  A UHV compatible stepping motor moves a 1 kg mass along the beam axis.

- ...is suspended on its center of mass and all the forces are applied on its baricentral horizontal plane to decouple the different degrees of freedom;

The Reaction Mass...

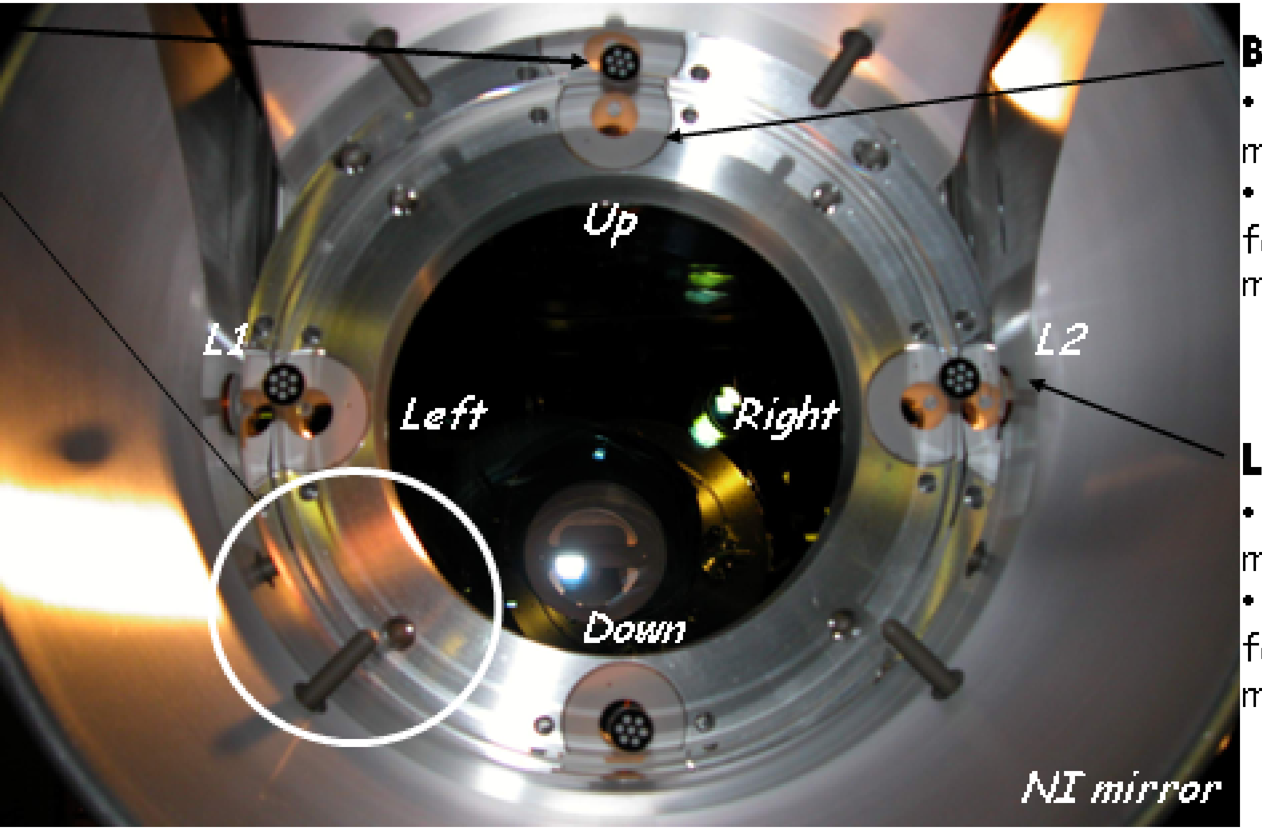
- ...controls the tilts θ_x, θ_y, and the translations along z and x;
- ...provides a safety structure for the mirror in case of suspension failure;

The reaction mass and the mirror must have the same center of mass to decouple the degrees of freedom;

The reaction mass of the Virgo Mirrors

Markers for the readout of the mirror local control system

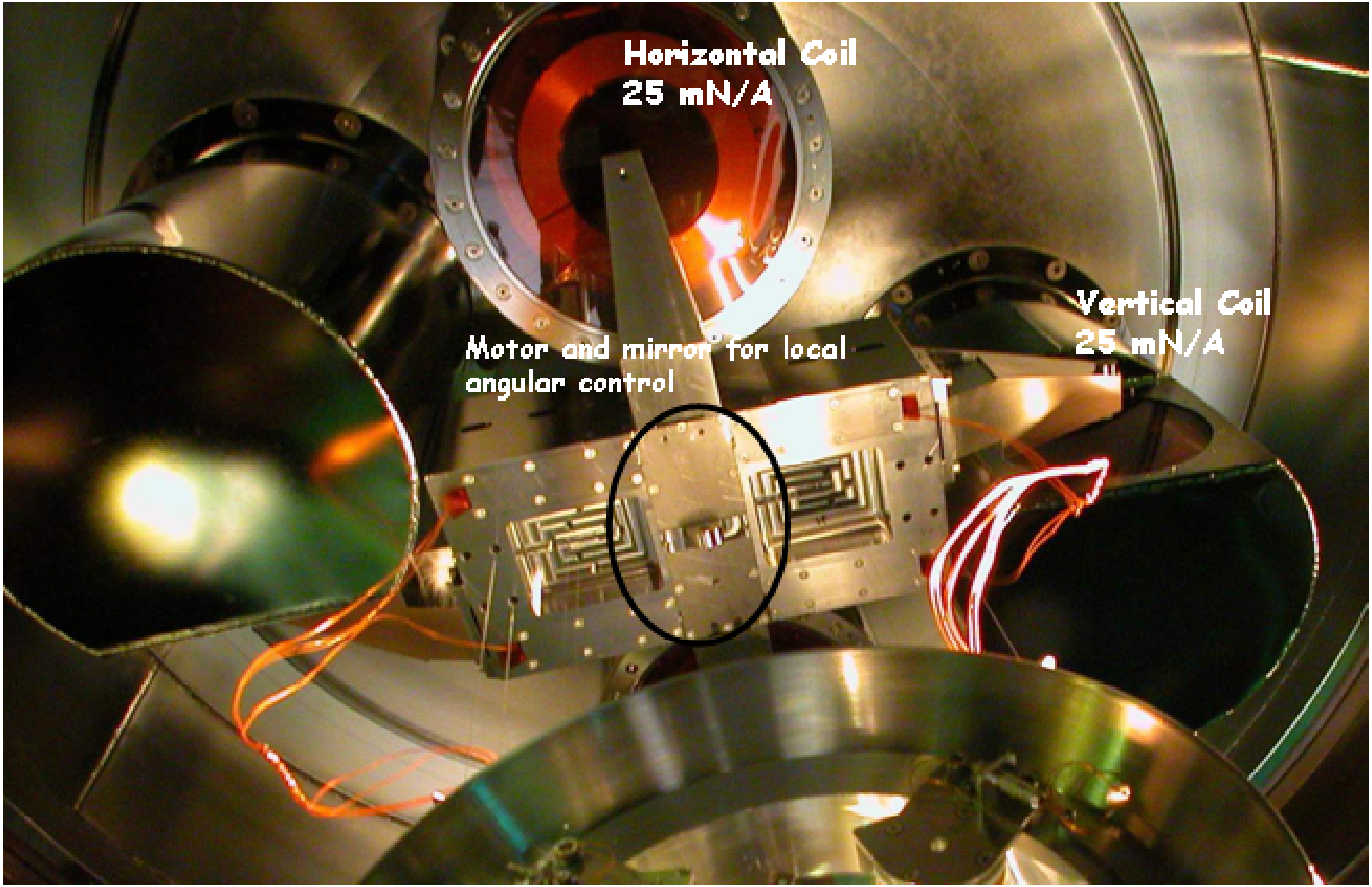
Safety stops
- made in PEEK, a UHV compatible plastic material;
- they prevent the mirror oscillations from damaging the coil supports;
- in case of suspension failure they prevent the mirror from falling out the reaction mass;



Back Coils
- Support in macor;
- Coupling factor of 10 mN/A

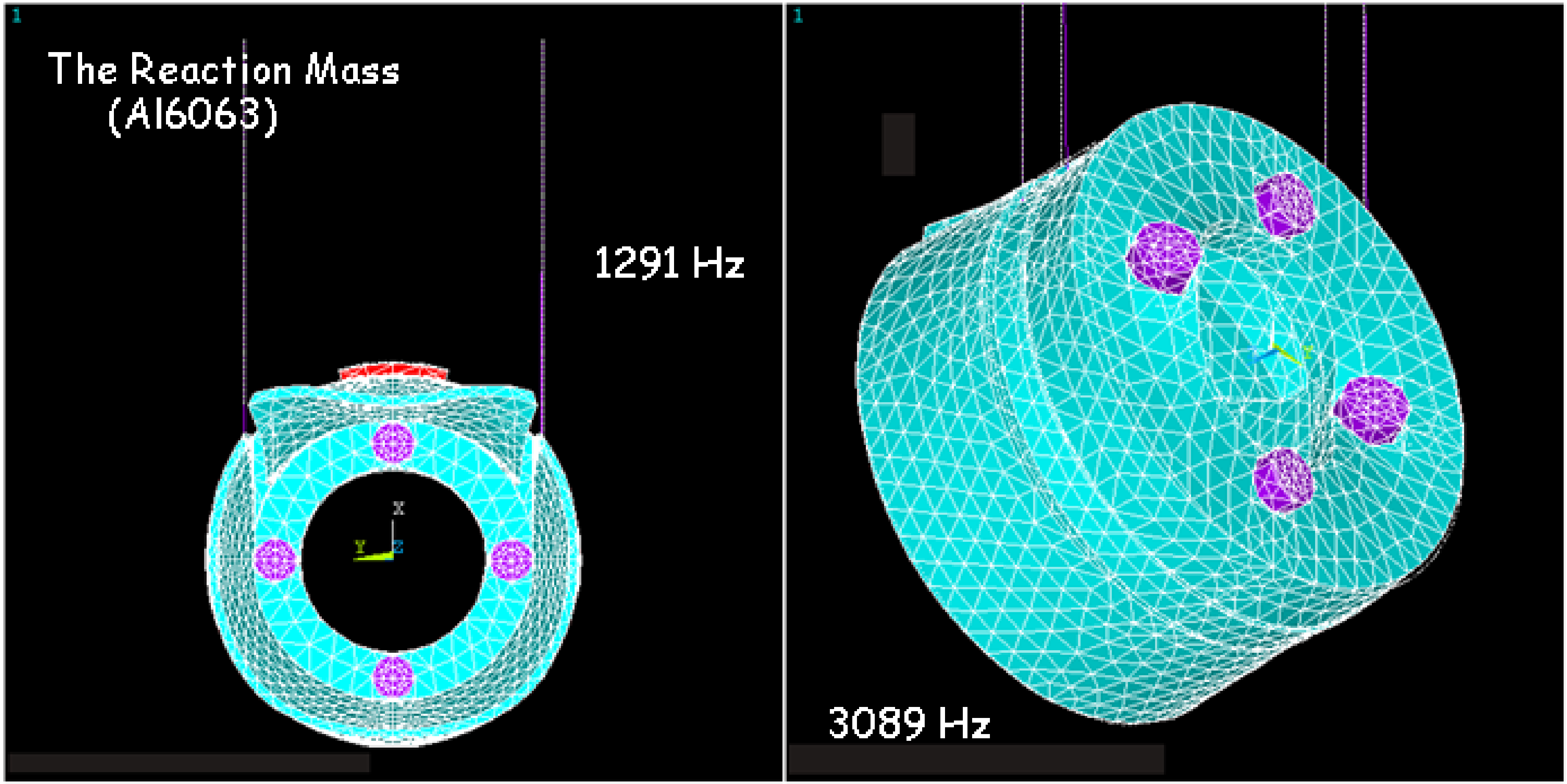
Lateral Coils
- Support in macor;
- Coupling factor of 5 mN/A

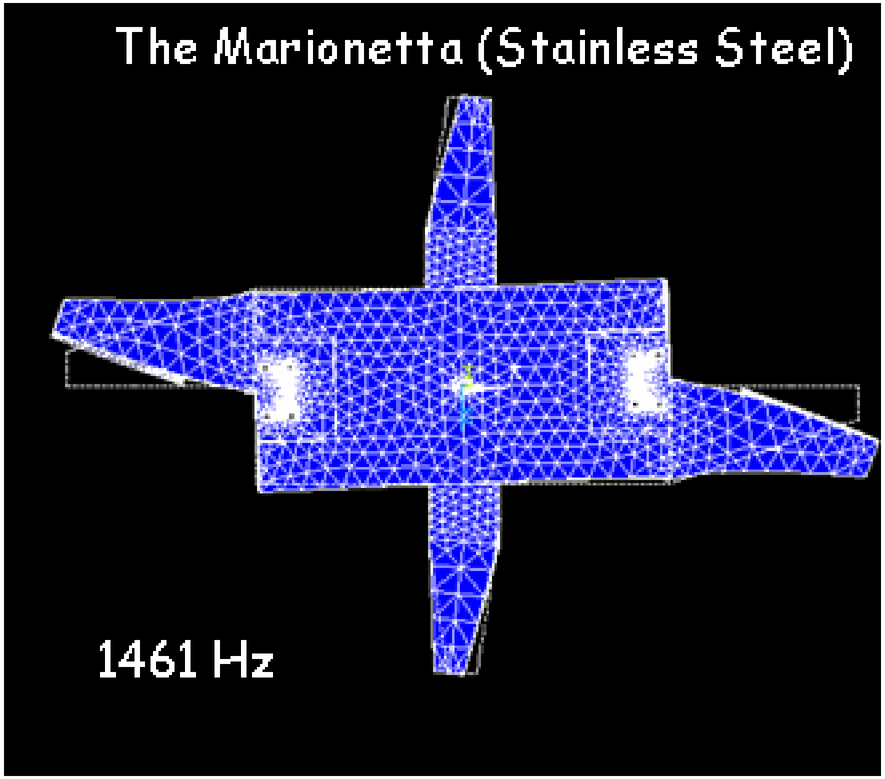
The marionetta for the Virgo Mirrors

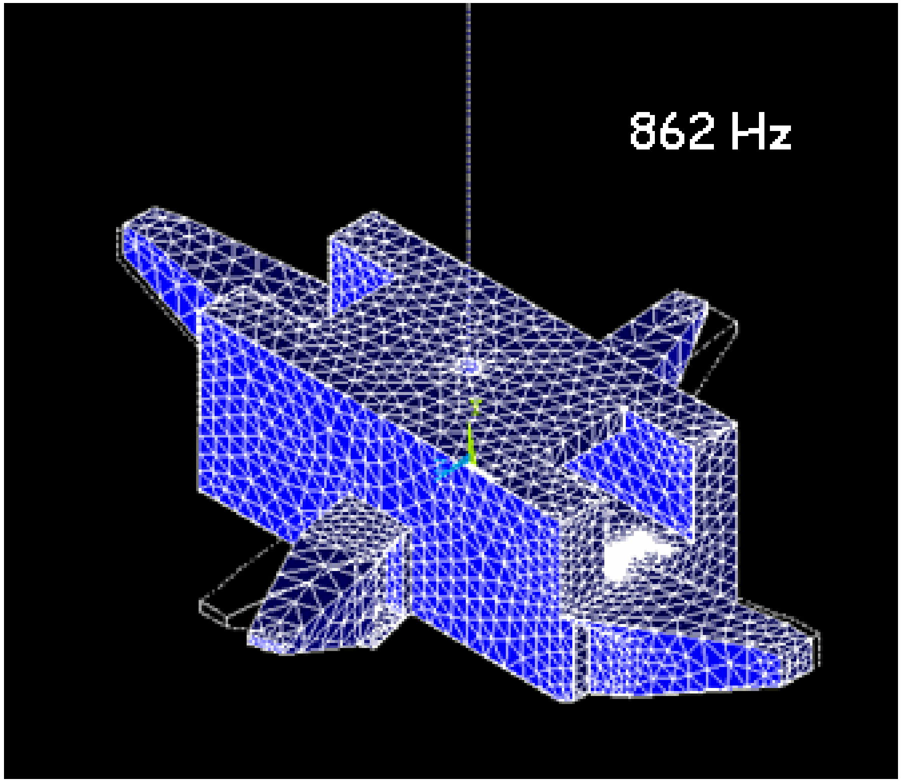


Finite elements simulations

- We have performed a finite element simulation of reaction mass and marionetta to study the internal modes that can couple, via the actuators, to the mirror motion, and to optimize the components design.

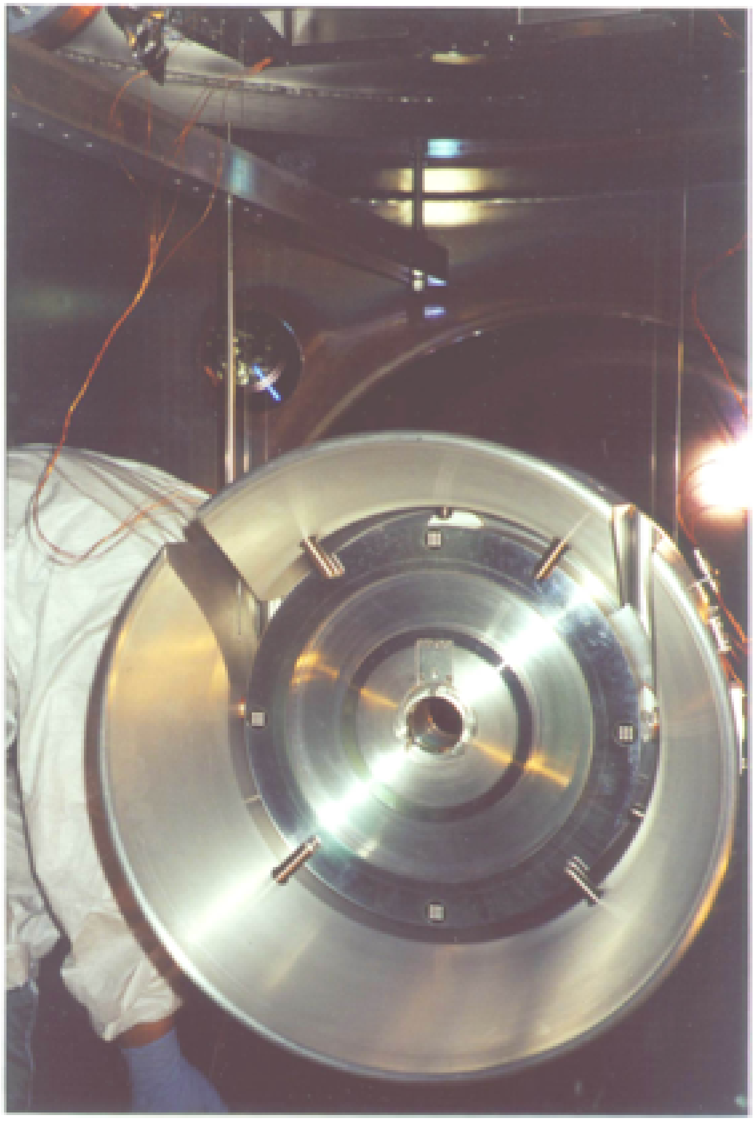



The Marionetta (Stainless Steel)
1461 Hz


862 Hz

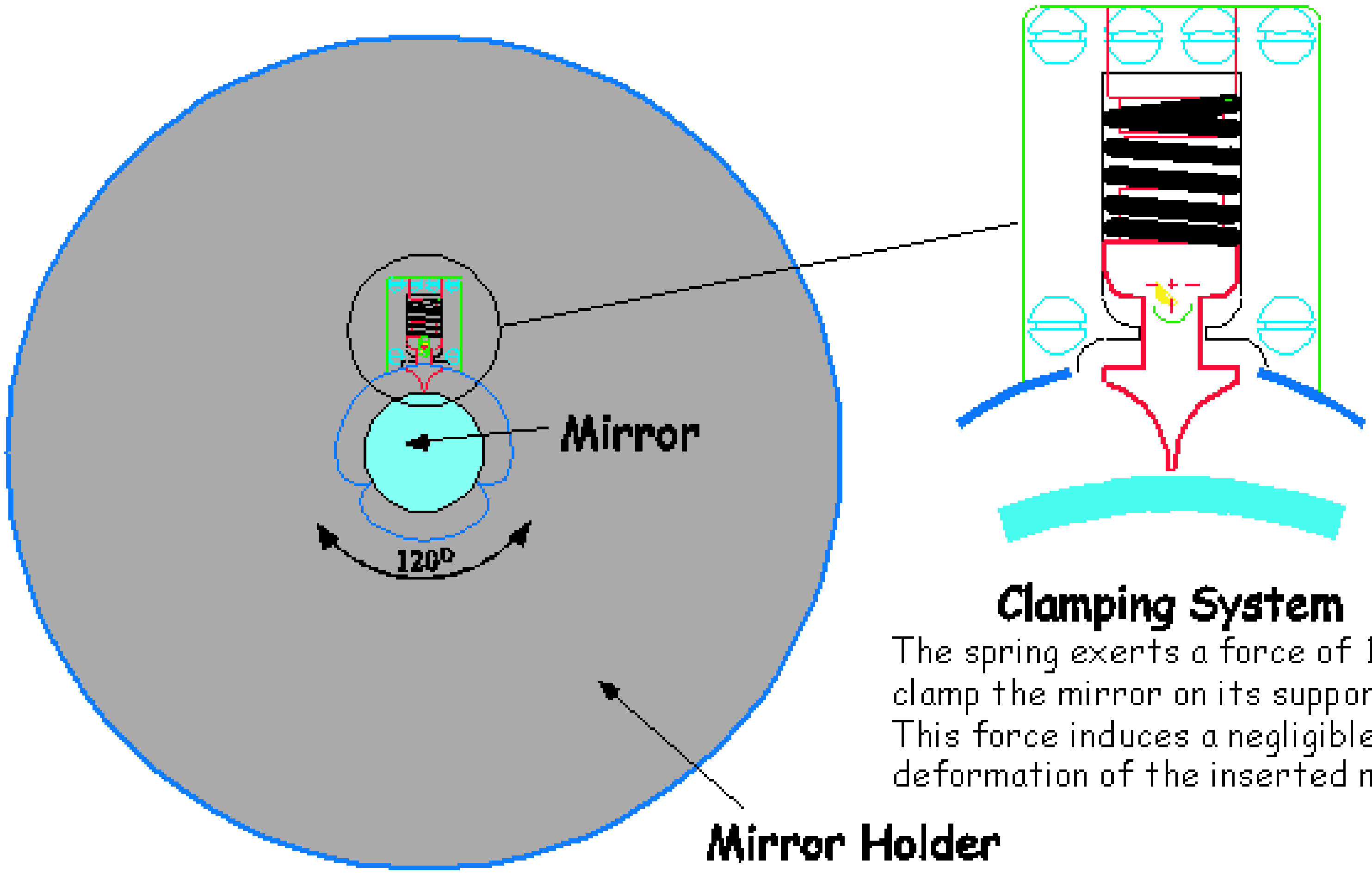
The CITF mirror payloads

- In the Central ITF all the mirrors have dimensions smaller than the final test masses;
- For this reason each mirror is held by an Al6063 support;
- The support has external dimensions as the Virgo mirrors;
- The use of the holder can modify the mechanical behavior of the mirror:
  - The mode shape
  - The overall losses
- These effect spoils the Virgo sensitivity curve;
- We have studied such effects* on a prototype;
- In the Virgo final ITF the Power Recycling mirror is held by an holder;



* F. Antonucci et al.,
"On the influence of a mirror holder to the thermal noise of gravitational wave interferometers",
to be published on P.L.A.

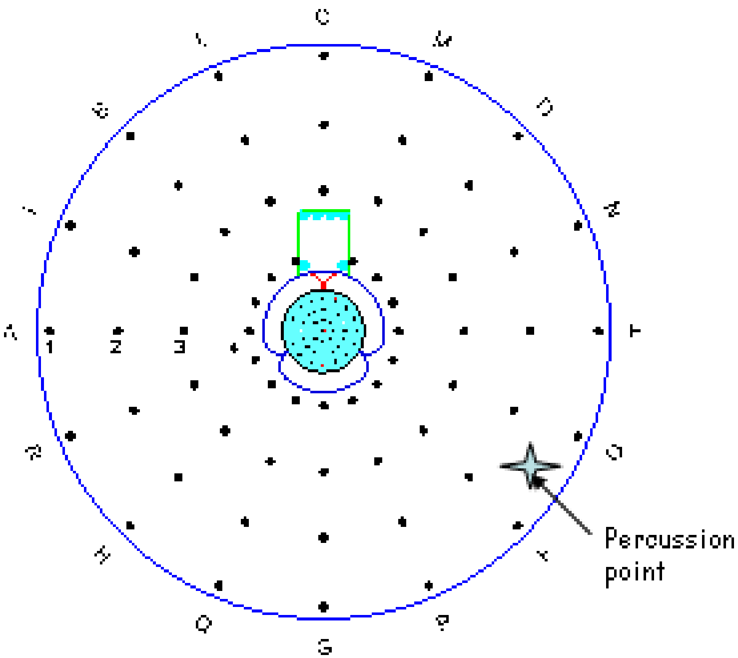
Scheme of the mirror holder



Clamping System

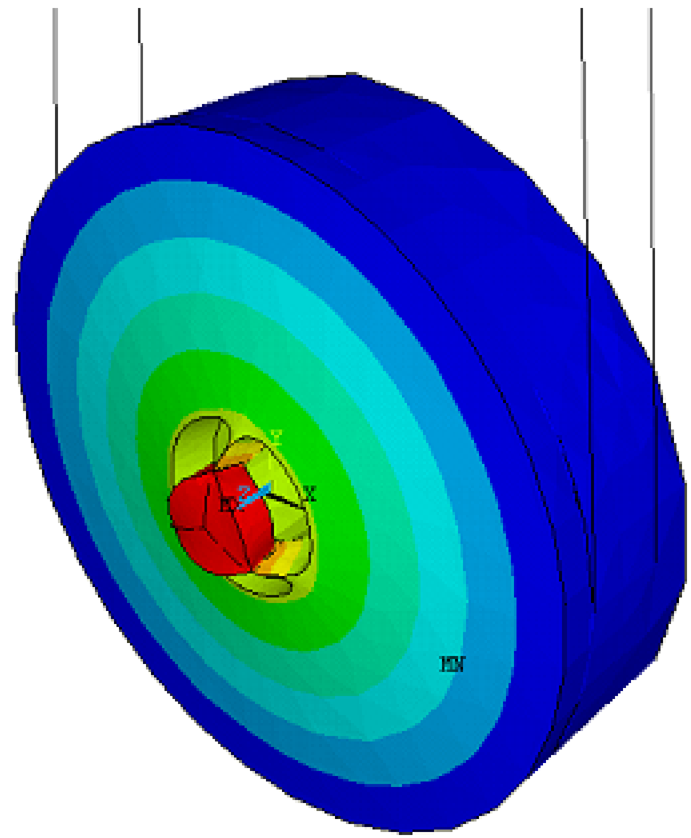
The spring exerts a force of 10 N to clamp the mirror on its support.
This force induces a negligible static deformation of the inserted mirror.

We have measured, on a prototype, the shape of the first symmetric mode, which mainly influences the sensitivity of Virgo.



- We have used an impulsive technique by hitting the holder on an assigned point with a calibrated hammer and measured the induced displacement along the z direction, at each point of the map, with an accelerometer.

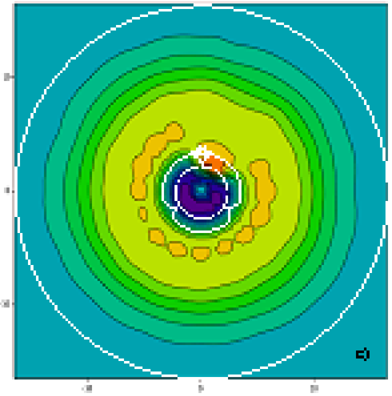
- The transfer functions between the percussion point and the detection points give informations on the mirror deformation, allowing us to reconstruct the mode shape.

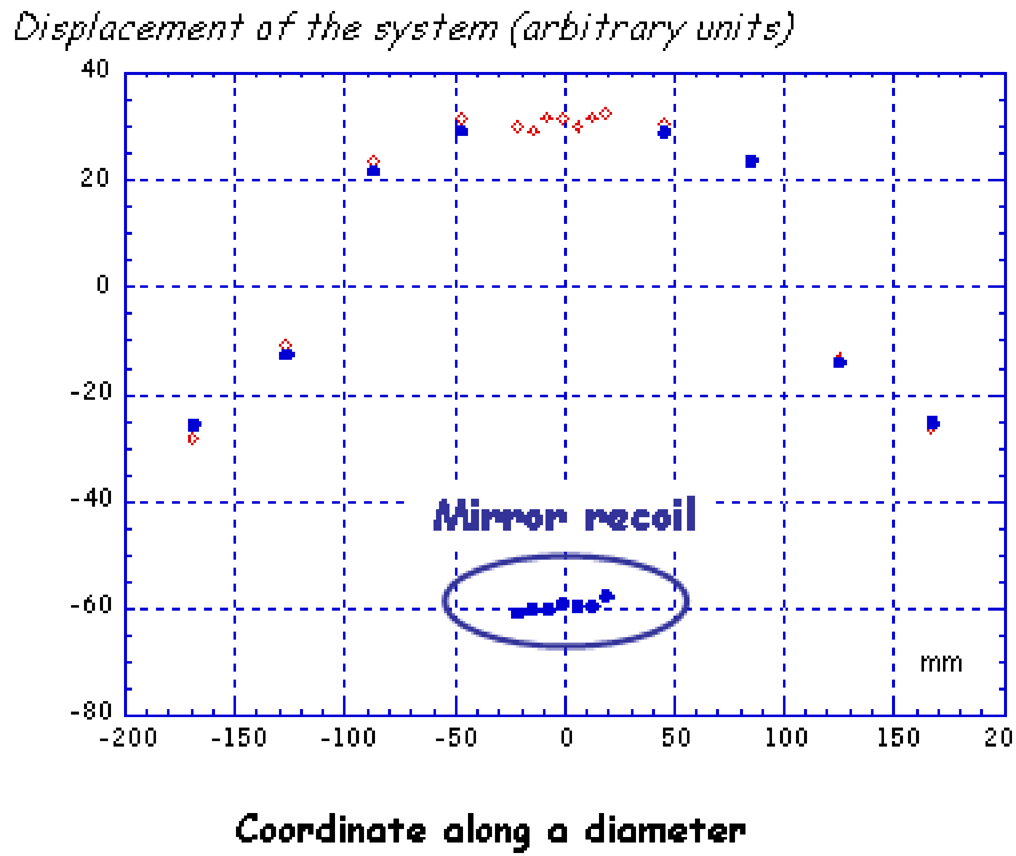


FEM Simulation of the First Symmetric Mode (5453 Hz)

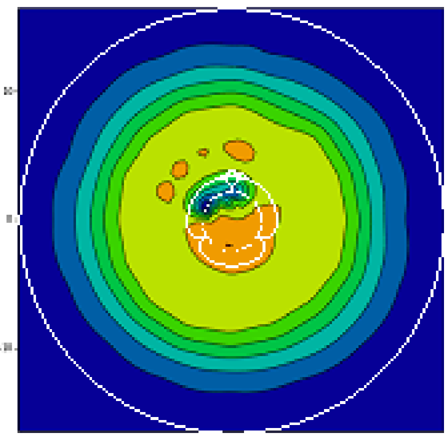
Mode Shape of the first symmetric mode

- Mirror inserted in the support and holded by the spring (CITF configuration)





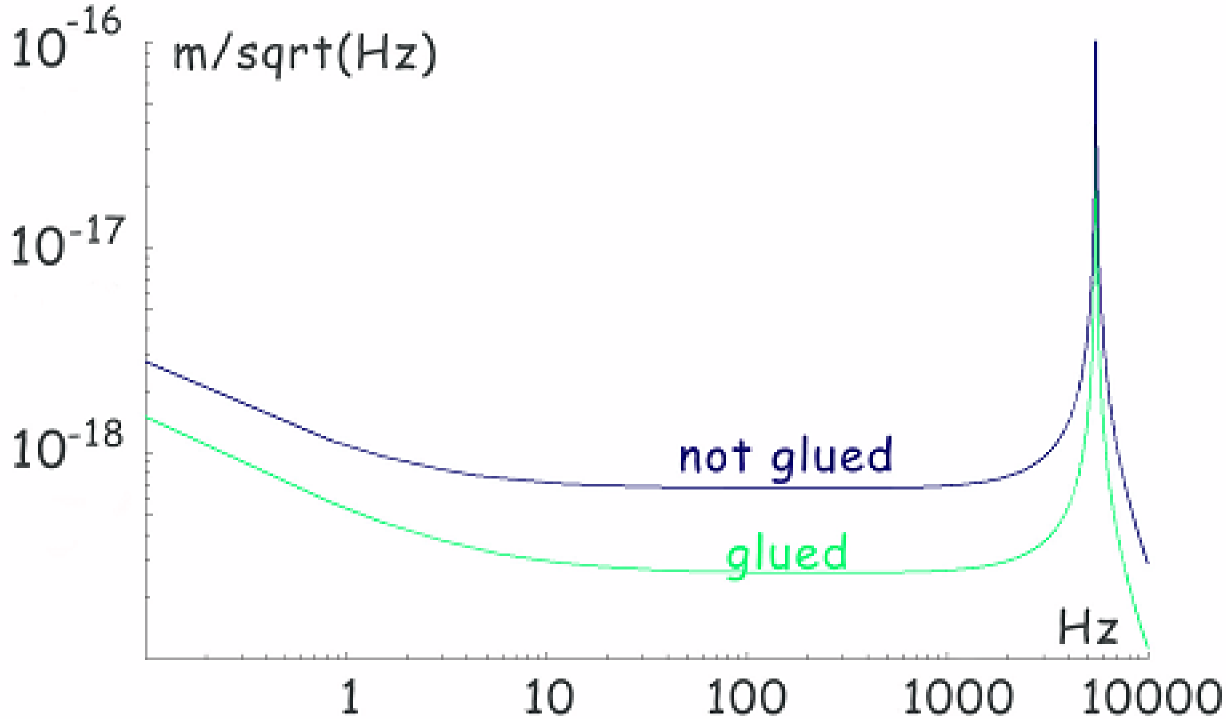
- **Mirror Glued to the blades**



From blue to red
(negative to positive displacement)

	Quality factor	M_{eff}	M_{eff} expected
CITF	(300 ± 50)	(3 ± 1) kg	
With glue	(600 ± 50)	(10 ± 4) kg	9 kg

- ***Making a comparison between the thermal noise spectral densities we can conclude that the sensitivity of the Virgo ITF could be spoiled by the holder..***



Non linear effects in the e.m. actuators

- Nonlinearities can interfere with the mirror control system because they induce unwanted modifications of the mirror position and give rise to spurious harmonics in the control signal;

- They are due to the electromagnetic couplings between the coils and the marionetta arms, or the coils and the mirror holders:

  - The magnetization of the metallic parts of the payload;

$$F_m = - \frac{\partial W(z)}{\partial z} = - \mu_o \chi_m I^2 \frac{\partial G(z)}{\partial z} = \underline{- \alpha_m I^2}$$

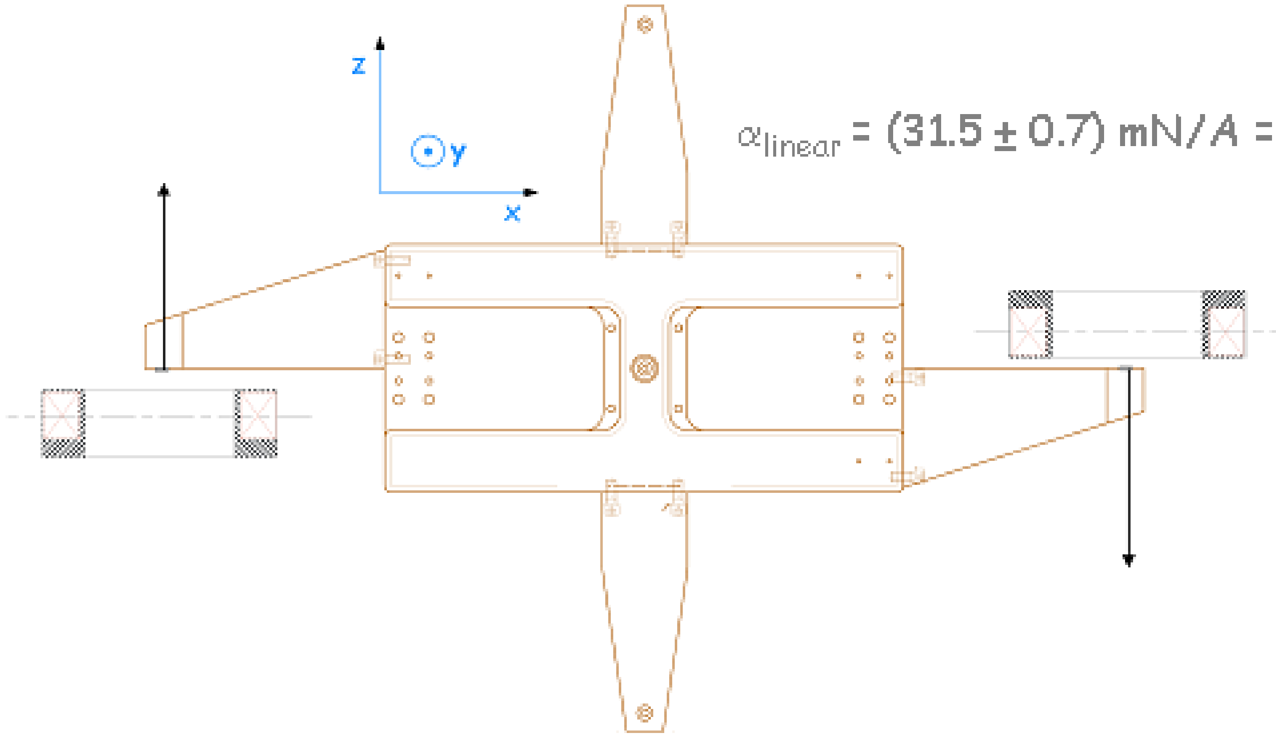
where $W(z) = \mu_o \chi_m (H(z))^2 \tau$ is the magnetic energy of the arms having a form factor τ and $(H(z))^2 \approx I^2 G(z)$ is the coil magnetic field squared. χ_m is the magnetic susceptibility;

  - The Focault currents in the metallic masses appear when an alternate current flows in the coils;

$$F_{eddy} = \sigma F(V)\, I(\omega t)\, I'(\omega t+\phi) = \underline{\alpha_{eddy}\, \omega\, I(\omega t)\, I'(\omega t+\phi)}$$

where $F(V)$ is a form factor taking into account the coils and arms geometry and σ is the electrical conductivity of the metallic mass.
The eddy current depends on the driving frequency ω.

We have studied the nonlinear effects on the marionetta of a prototype of the last stage suspensions used in the CITF with arms made of four kinds of materials.

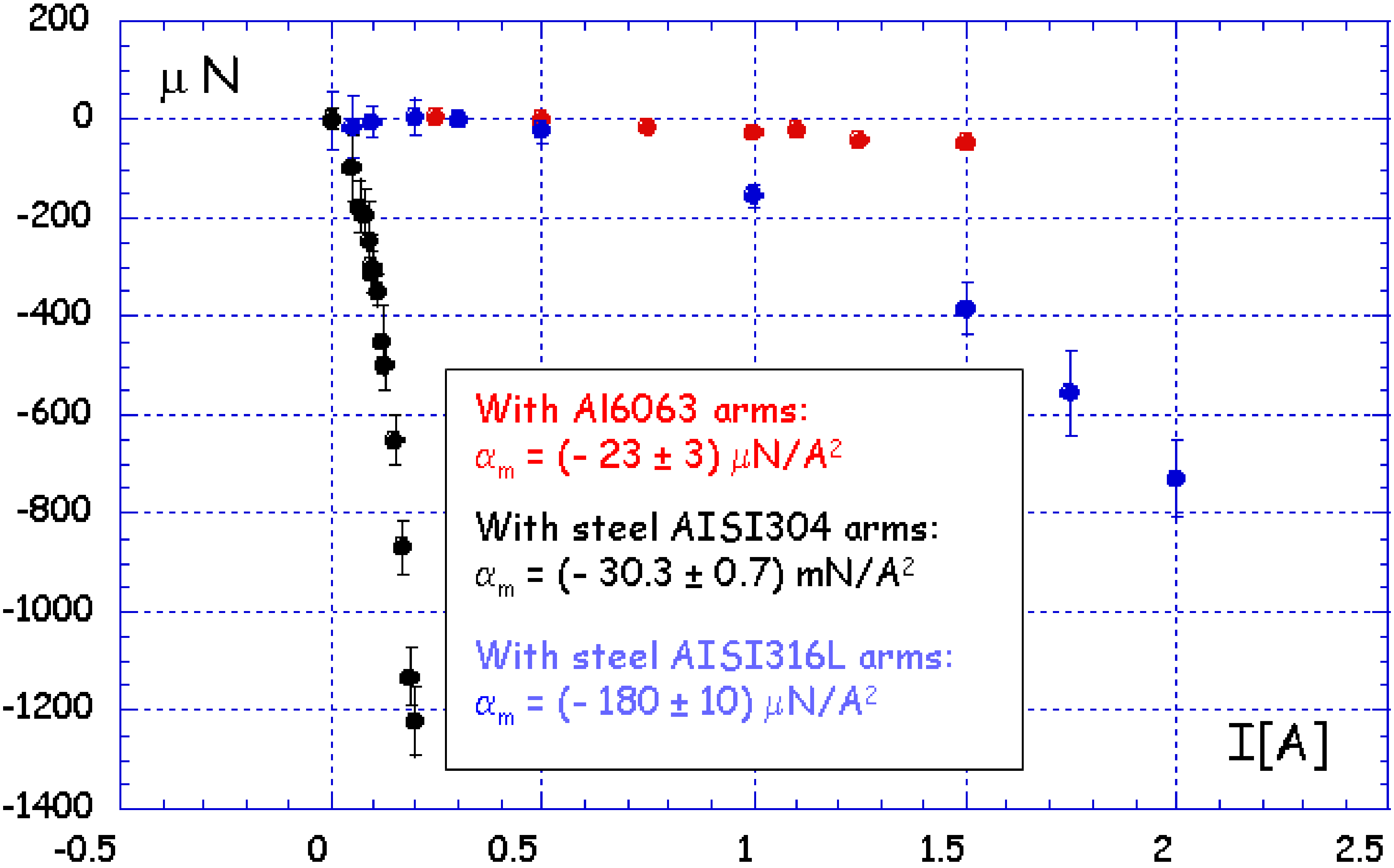


α_{linear} = (31.5 ± 0.7) mN/A = (319 ± 3) mrad/A

<u>DC measurements</u>. We have measured the static torsion occurring when a static current flows in the vertical coils. The magnets were not installed on the marionetta arms.

<u>AC measurements</u>. We have measured the static torsion occurring when a sinusoidal current flows in the vertical coils. The magnets were not installed on the marionetta arms.

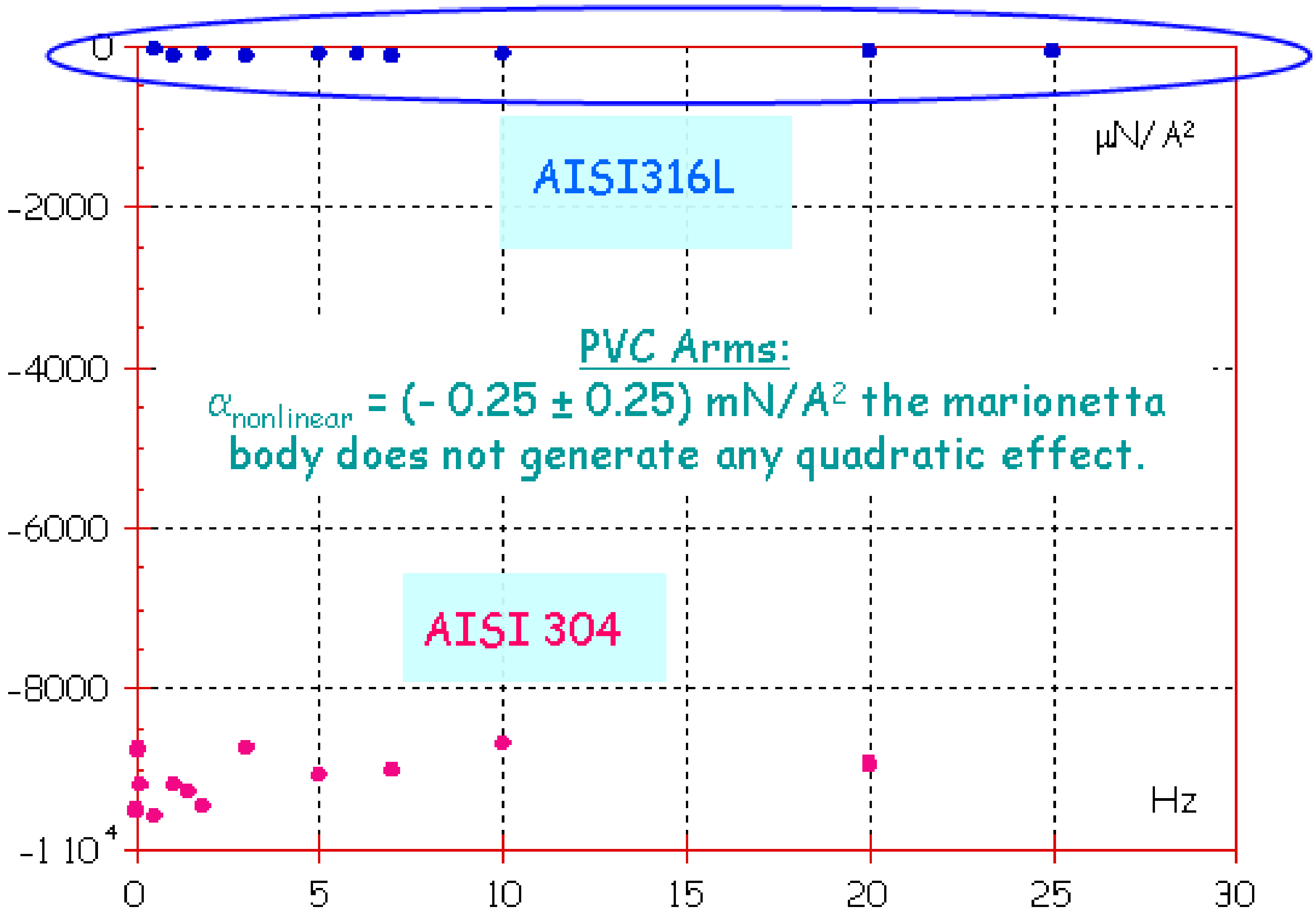
DC Measurements. When a static current flows in the coils:



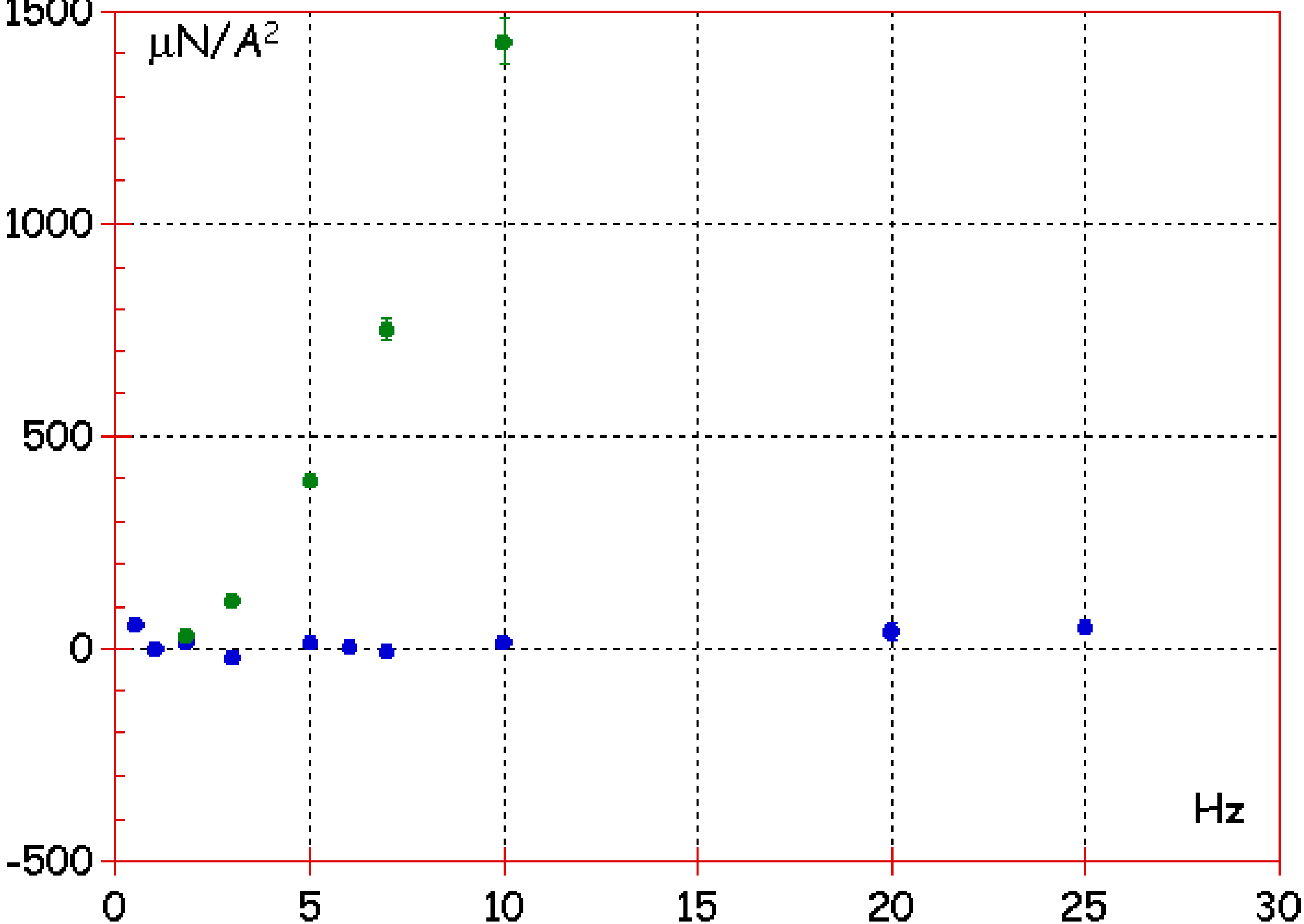
AC measurements

When a sinusoidal current $I(t)=I_o \sin(\omega_o t)$ flows in the coils, a static torsion, given by the combination of both effects, can be observed and the force exerted by each coil is:

$$F_{nonlinear} = (1/2)(\alpha_{eddy}\ \omega_o \sin\phi - \alpha_m) I_o^2$$



Eddy current residual effect on Steel AISI 316L arms compared with Al6063 eddy currents effect.



Discussion

AISI304 Arms (CITF):

DC measurements: α_m = (- 30.3 ± 0.7) mN/A^2

AC measurements: $\alpha_{nonlinear}$ = (- 20 ± 1) mN/A^2

due to unexpected magnetization of the material

Al6063 Arms:

DC measurements: α_m = (- 23 ± 3) μN/A^2 magnetization

AC measurements due to a strong eddy currents effect.

AISI316L Arms:

DC measurements: α_m = (- 180 ± 10) μN/A^2

AC measurements due to eddy currents and magnetization.

Eddy current effect ≈ 2 μN/A^2/Hz

Conclusions

In the final ITF the arms are made in the amagnetic steel AISI316L, with $\chi_m = 5\ 10^{-3}$ $\rho = 1/\sigma = 4.5\ 10^{-7}\ \Omega$/m.

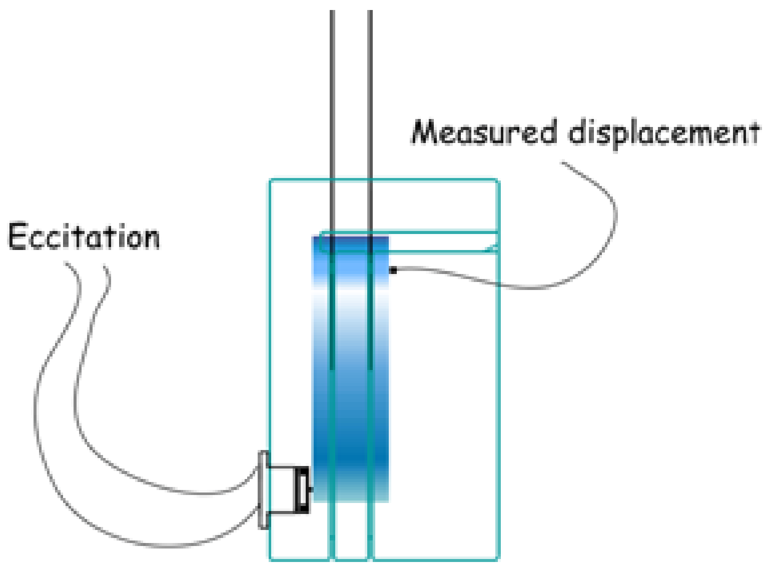
$F_{magn.}$ = 1/10 Fcoils @ I=18 A

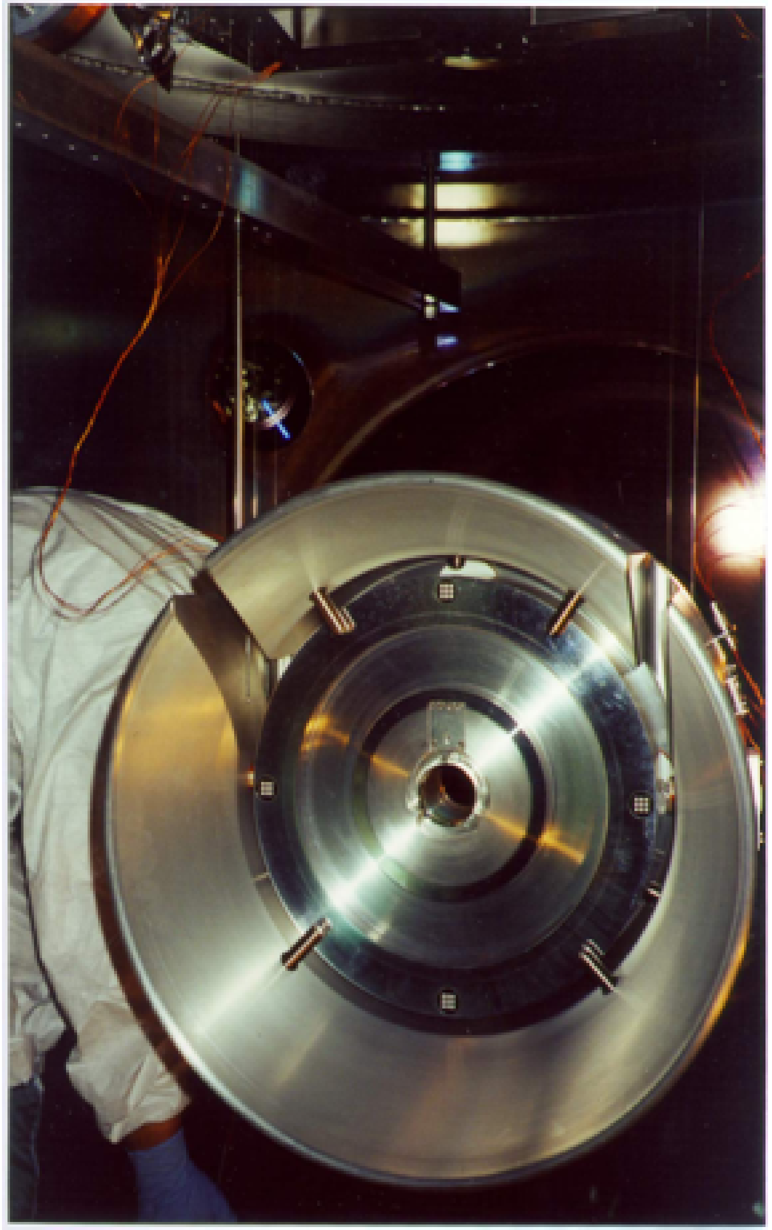
$F_{e.c.}$ (1 Hz) = 1/10 Fcoils @ I=1600 A

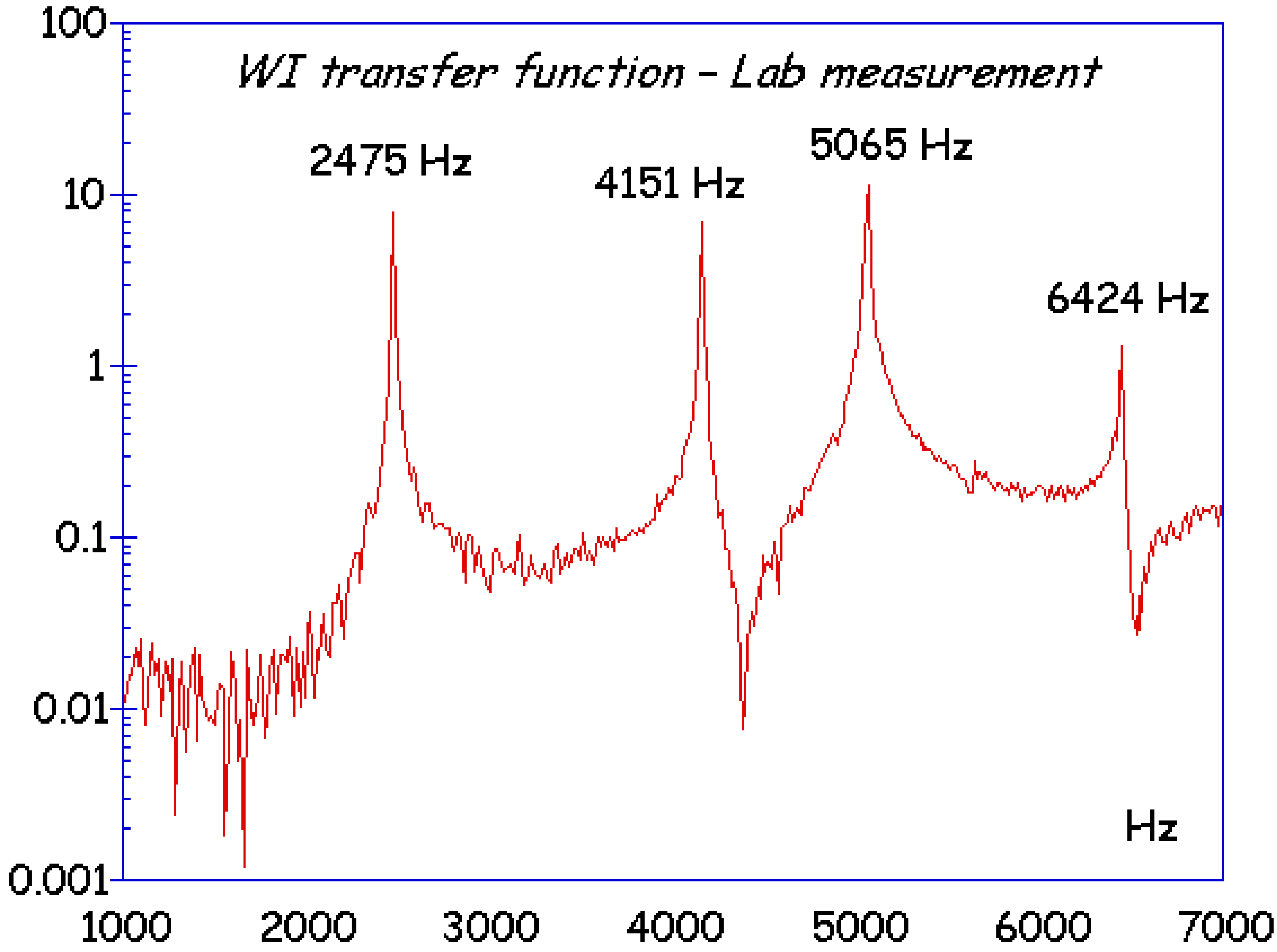
Identification of the West input mirror internal modes in the CITF

Some preliminary results

- We have identified the WI mirror internal modes performing some measurements in our laboratory, after CITF disassembling.
- We excited the mirror + holder system from the reaction mass back down coil and measured the displacement along its axis with an accelerometer.
- We compared the results with the CITF high frequency transfer function measured during E4.



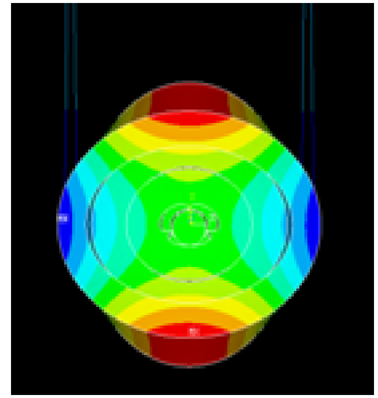


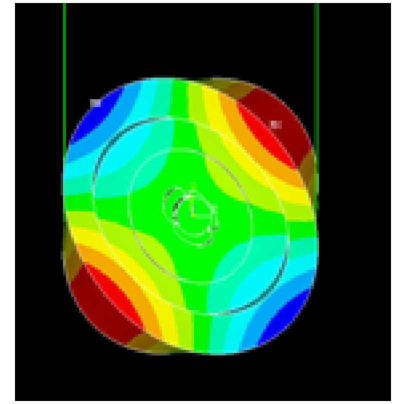


We have measured the mode shape of the internal frequencies

First Asymmetric (0,2)
2475 Hz

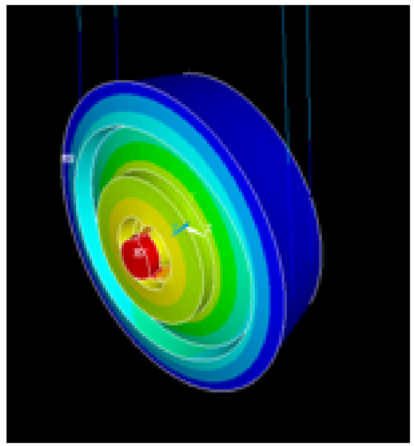
simulation 2441 Hz





First Symmetric (1,0)
4151 Hz

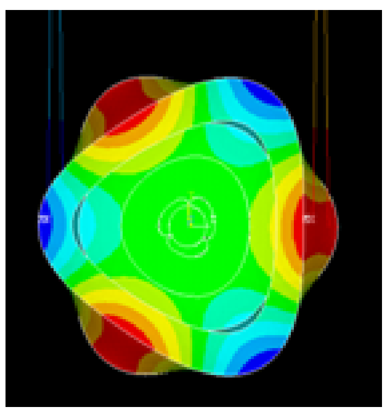
simulation 4163 Hz



(0,3)

5064 Hz

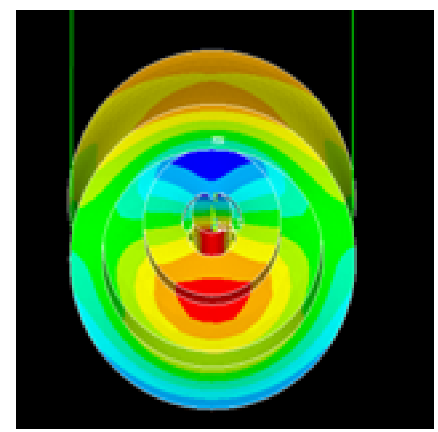
simulation 5144 Hz



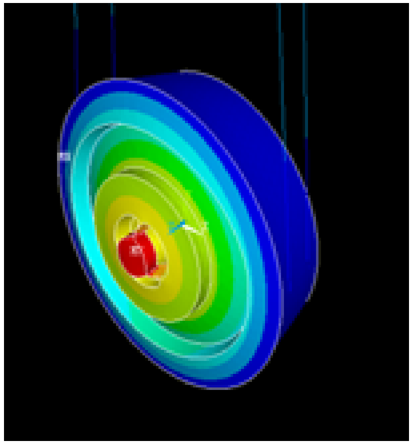
(1,1)

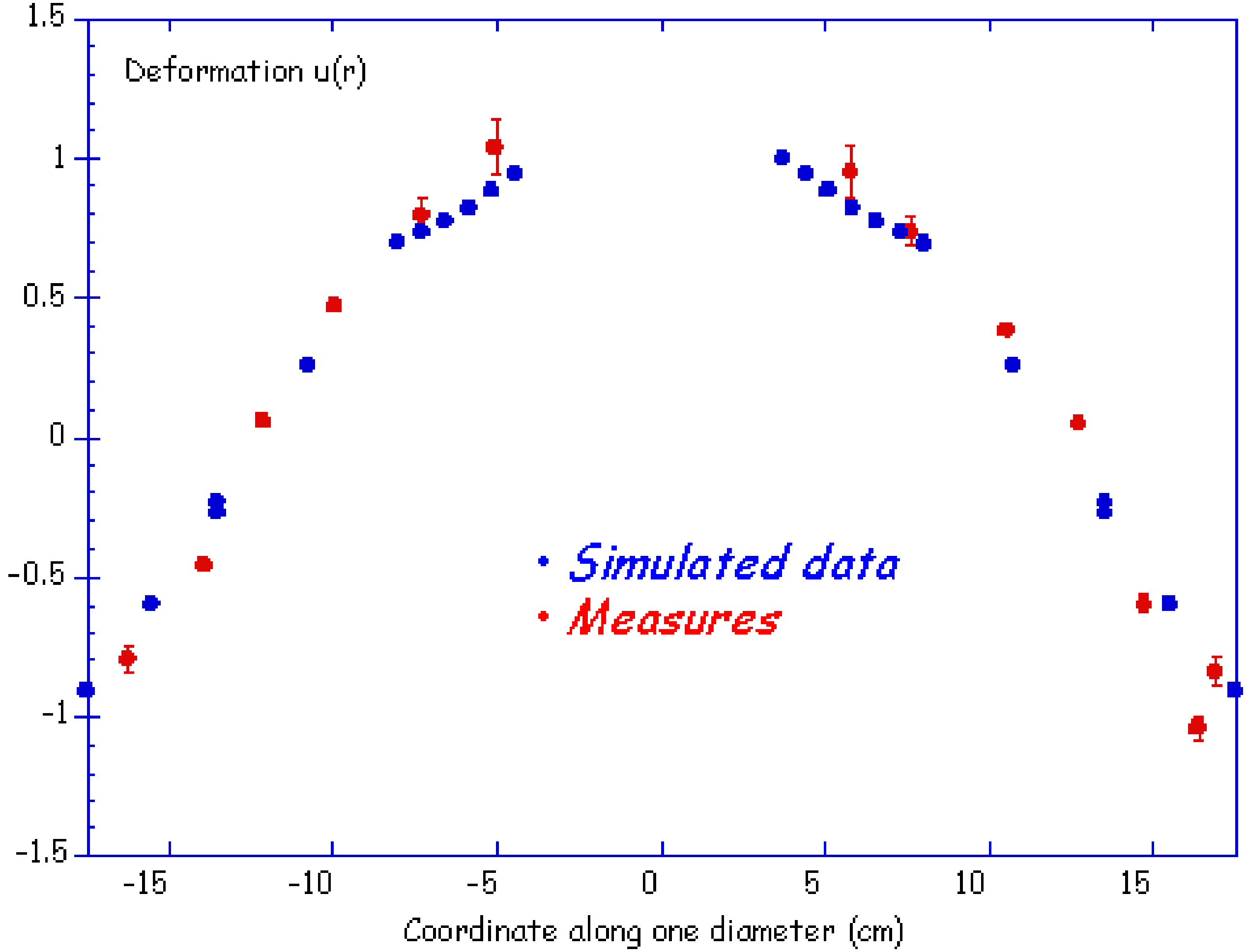
6424 Hz

simulation 6668 Hz



Profile of the symmetric mode 4151 Hz





Effective Mass

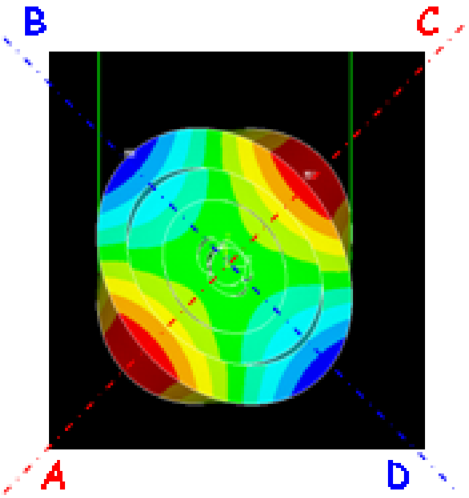
$$M_{eq} = \frac{\langle u^2 \rangle}{u_{abs}^2} M_{tot}$$

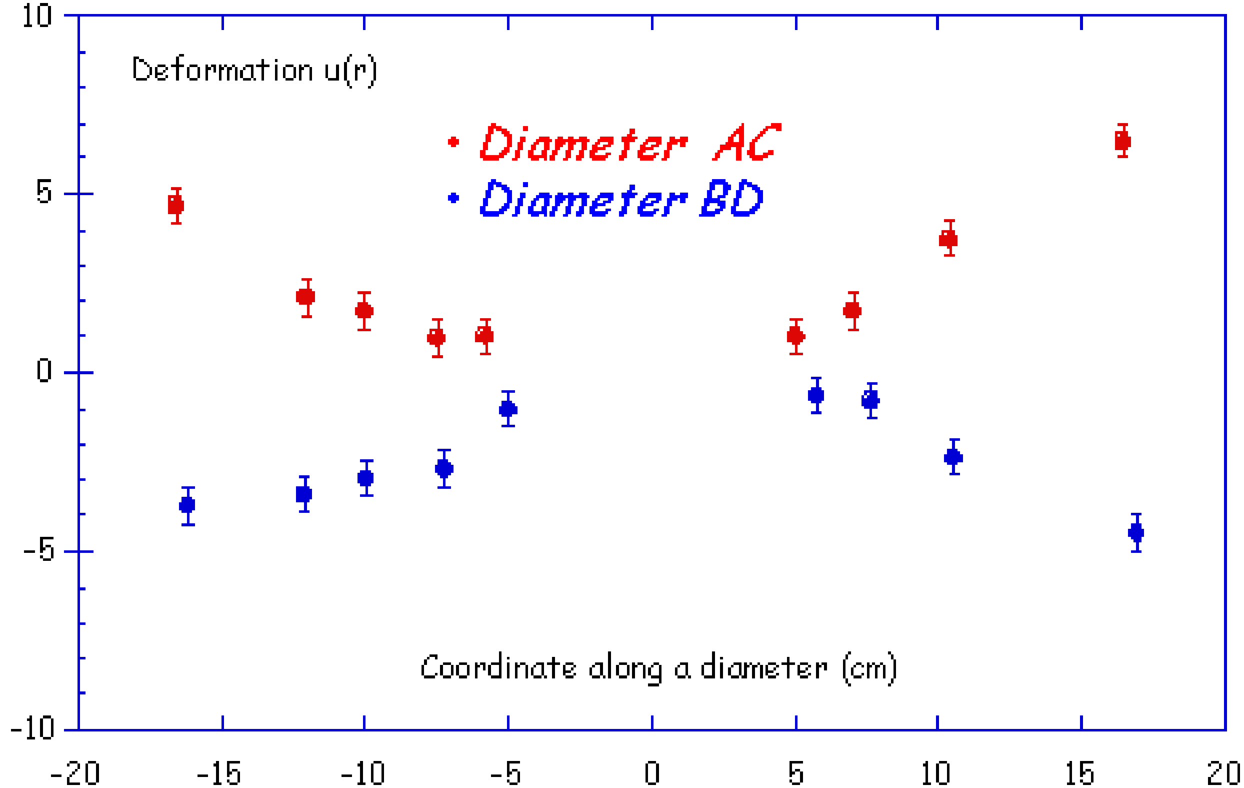
$$\langle u^2 \rangle = \frac{1}{V} \int_V u^2 \, r \, dr \, d\theta$$

$$M_{eq} = (7.0 \pm 0.5) kg$$

from the simulation we have obtained: *Meq* = 7.56 kg

Profile of the asymmetric mode 2475 Hz



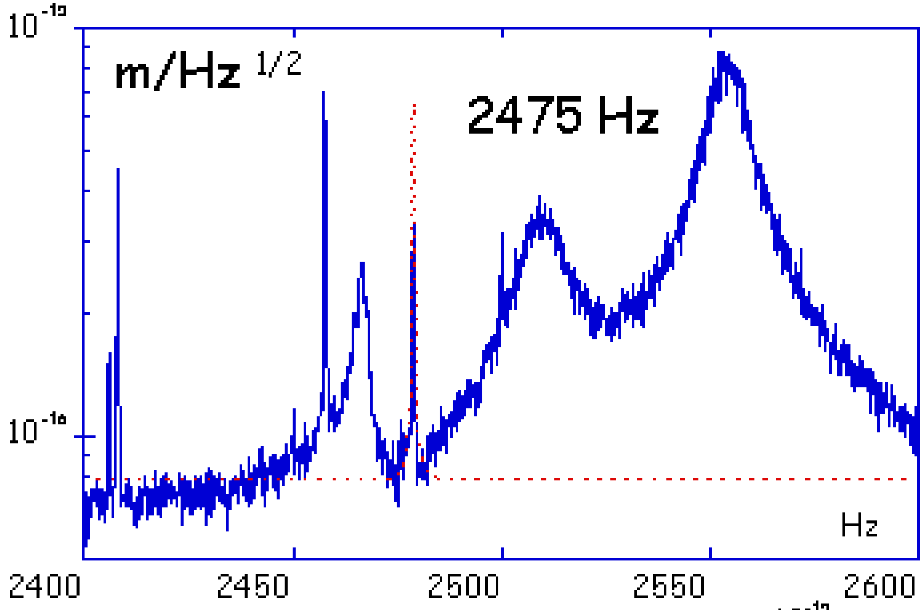


Effective Mass

$$M_{eq} = \frac{< u^2 >}{u_{abs}^2} M_{tot}$$

$$< u^2 > = \frac{1}{V} \int_V u^2 r dr d\theta$$

$$M_{eq} \simeq (100 \pm 50) kg$$



Comparison of the E4 displacements noise spectrum with the thermal noise contributions computed using the Lab measurements results.

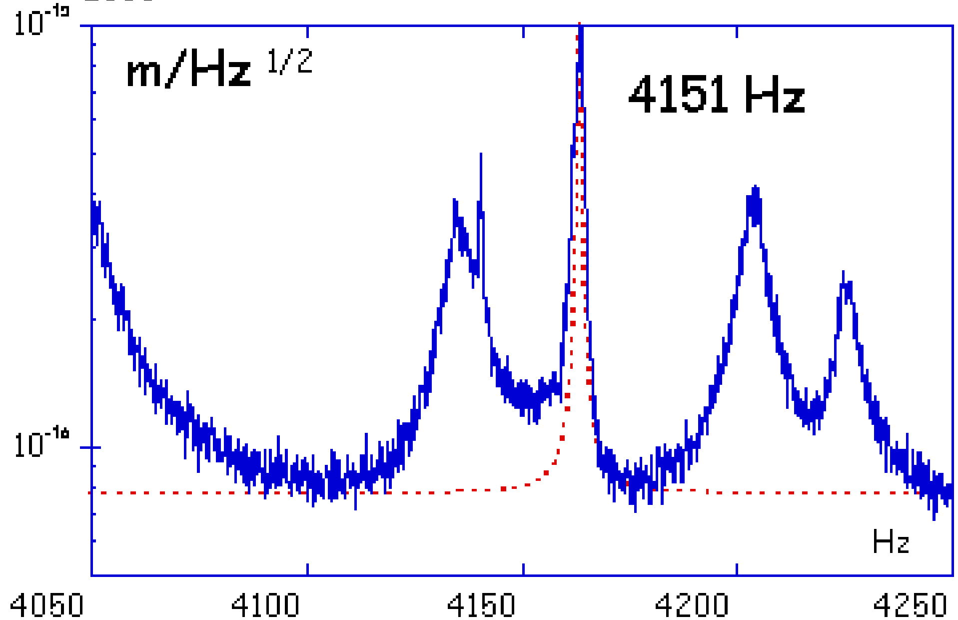
Theoretical computation

E4 Noise Data

The estimated peaks are of the same order of magnitude of the data:

6.0 10^{-16} m/Hz $^{\frac{1}{2}}$ @ 2475 Hz

1.0 10^{-15} m/Hz $^{\frac{1}{2}}$ @ 4151 Hz



Conclusions

- We have described the last stage suspensions of the mirrors of Virgo.

- The limits experienced in the CITF has helped us to improve to the set up for final configuration:
  - Nonlinearities reduced;
  - Mirror holder for the PR mirror optimised;

- We have identified and characterised the CITF WI mirror internal modes;
  - The equivalent mass of the first two modes was computed. <u>The value is compatible with the hypothesis that the peaks in the E4 noise spectrum are due to thermal motion.</u>