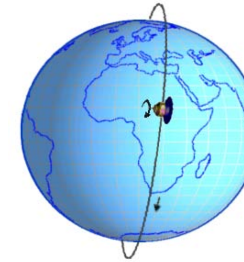


GGG

Un accelerometro differenziale in rotazione veloce per la verifica del principio di equivalenza

Anna Nobili e Raffaello Pegna

INFN Sezione di Pisa, 22 Giugno 2011

agenzia spaziale italiana

IN SUPREMÆ DIGNITATIS 1343

INFN Istituto Nazionale di Fisica Nucleare

Why testing the Weak Equivalence Principle? Why in space?

- The Weak Equivalence Principle is the founding pillar of General Relativity

- EP tests are the only ones which test GR for composition dependence

- Evidence of EP violation would prove the existence of a new composition dependent force of Nature and make for a scientific revolution (by comparison, a geodetic or Lense Thirring precession or light rays deflection different from Einstein's prediction would simply call for another metric theory of gravity slightly different from GR…)

.. aim at higher sensitivity whenever the possibility for an improvement arises

<u>In low orbit around the Earth:</u>

- 3 orders of magnitude stronger signal
- weightlessness
- experiment isolated in space

State of the art

36 yr

14 yr

Authors	Apparatus	Source mass	Materials	$\eta \equiv \Delta a / a$
Eötvös et al. ≈1900 collected in Ann. Phys. **1922**	Torsion balance. Not rotating. No signal modulation	Earth	Many combinations	$10^{-8} \div 10^{-9}$
Roll, Krotkov & Dicke Ann. Phys. **1964**	Torsion balance. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Au	$(1.3 \pm 1)\mathrm{x}10^{-11}$
Braginsky & Panov JETP **1972**	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9)\mathrm{x}\mathbf{10^{-12}}$
E. Fischbach et al.: "Reanalysis of the Eötvös Experiment" PRL 1986				
Eöt-Wash, PRD **1994**	Rotating torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5)\mathrm{x}\mathbf{10^{-12}}$
			Be – Al	$(-0.2 \pm 2.8)\mathrm{x}10^{-12}$
Eöt-Wash, PRL 1999	Rotating torsion balance. 1hr to 36' modulation	Sun	Earthlike/ Moonlike	$\approx 10^{-12}$ (SEP $1.3\mathrm{x}10^{-3}$)
Eöt-Wash, PRL **2008**	Rotating torsion balance. 20' modulation	Earth	Be – Ti	$(0.3 \pm 1.8)\mathrm{x}\mathbf{10^{-13}}$

GG: aiming at an improvement from 10^{-13} to 10^{-17}

- Slowly rotating torsion balances have achieved:

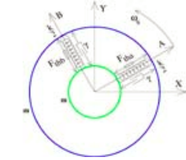
$$(\Delta a)_{TB} = 10^{-16} g \quad \Rightarrow \quad \eta_{TB} = 10^{-13}$$

- In order to improve the EP test by 4 orders of magnitude GG must be able to sense differential accelerations between the test masses only one order of magnitude smaller than torsion balances, simply because in space the signal is 3 orders of magnitude stronger:

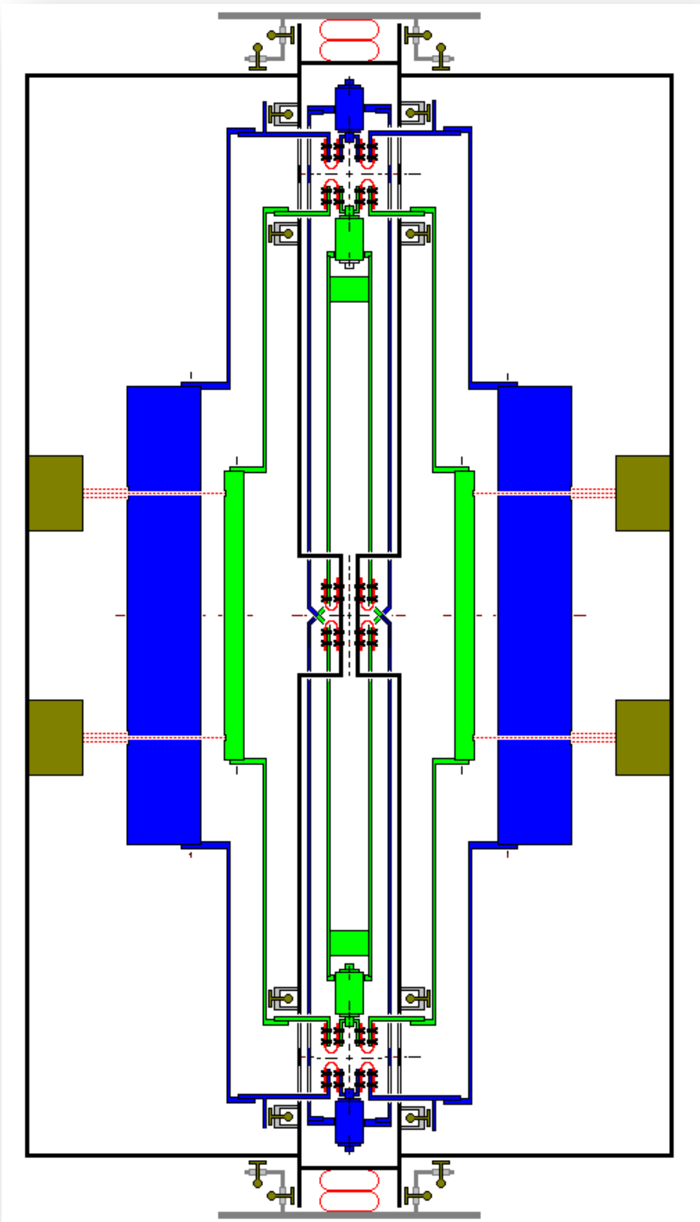
$$(\Delta a)_{GG} = 10^{-17} g \quad \Rightarrow \quad \eta_{GG} = 10^{-17}$$

Collaboration ongoing with JPL to submit GG to the next EXPLORER call of NASA as a NASA led small mission with ASI partnership (GG not submitted previous EXPLORER call last February because a key technology −FEEP thrusters− would not be tested on time by LISA/PF −more than 2 yrs launch delay of LISA/PF announced in January; NASA has withdrawn from LISA shortly afterwards)

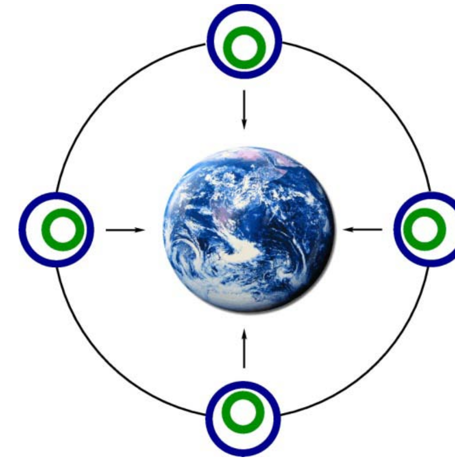
GG mission duration can be ensured by cold gas thrusters (baseline thrusters for GAIA).
For next NASA call:
– adjust mission design and error budget with new thrusters
– improve GGG prototype sensitivity at 1.7×10^{-4} Hz (frequency of EP violation signal in space)

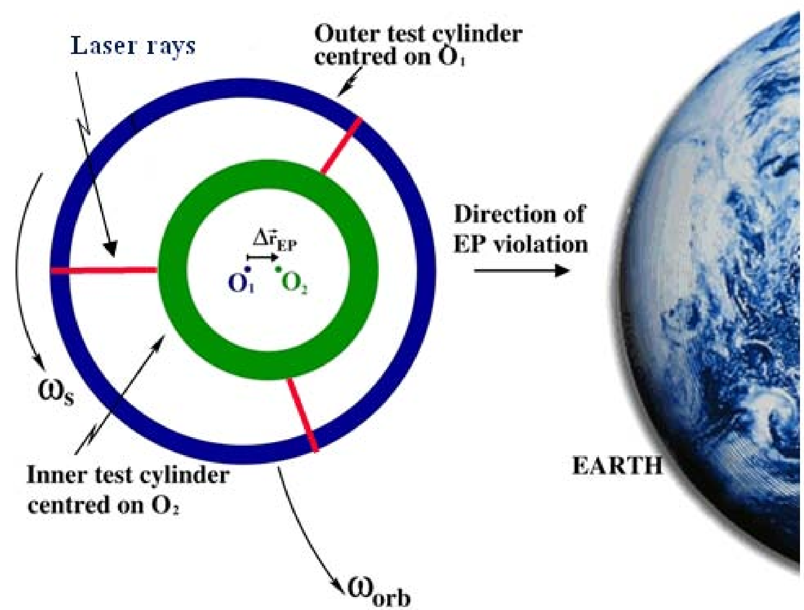


The GG experiment in space (I)



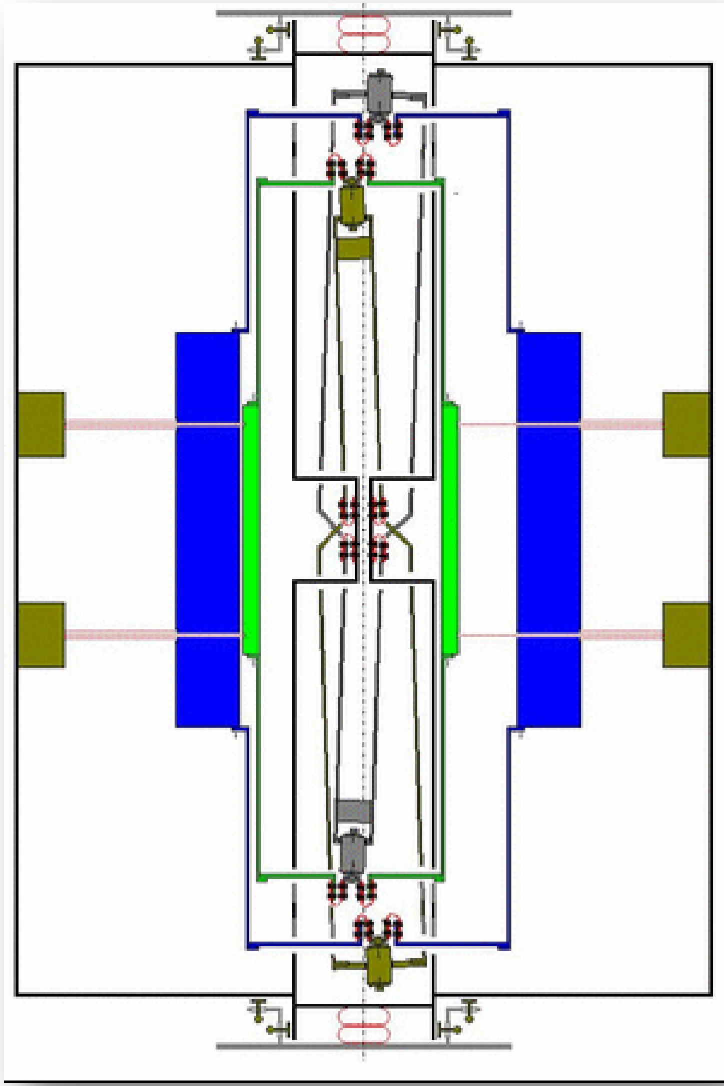
Put the concentric cylinders in LEO and spin around the symmetry axis so that the sensitive plane can detect differential accelerations acting in the orbit plane, e.g. an EP violation…





The GG experiment in space (II)

$\vec{\omega}_s$ $\omega_s = 2\pi/1\,\mathrm{s}$



$\vec{n}$ $n = 2\pi/5800\,\mathrm{s}$

$\vec{r}$

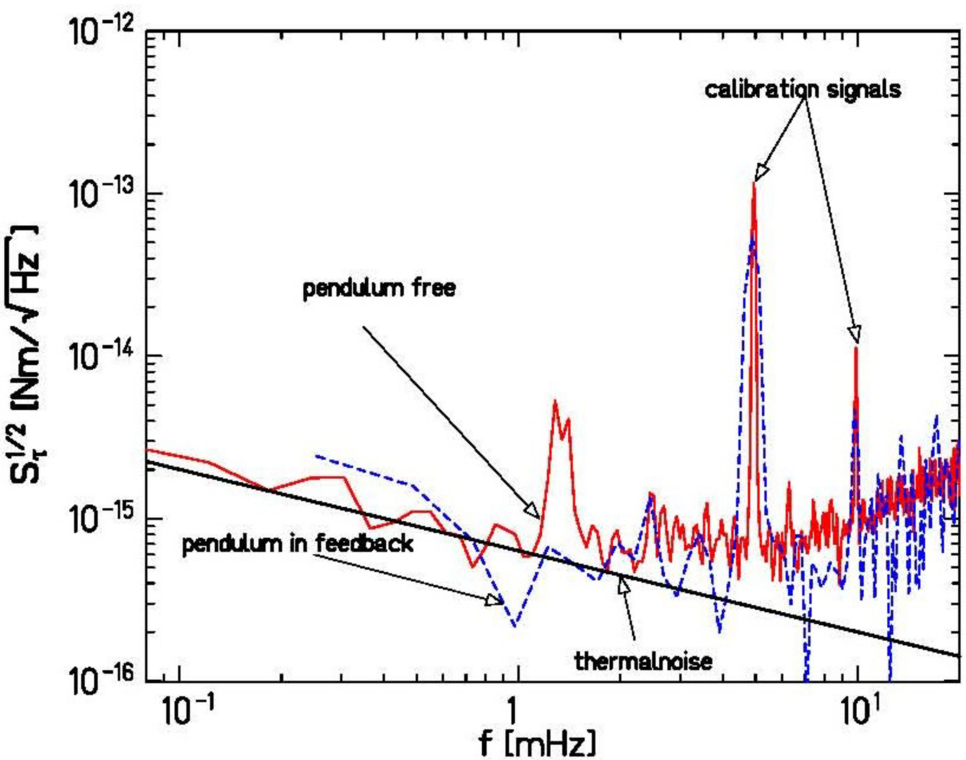
$r = R_\oplus + 600\,\mathrm{km}$

$$\eta = 10^{-17} \;,\; \omega_n = 2\pi/540\,\mathrm{s} \Longrightarrow \Delta r_{EP} \simeq 0.5\,\mathrm{pm}$$

Laser read-out (withJPL laser gauge tested for SIM)

Thermal noise & integration time

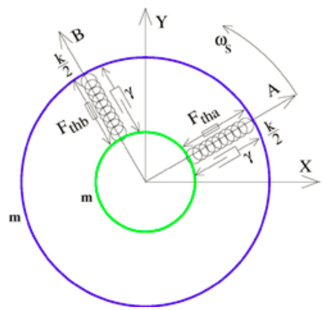
- Low thermal noise is crucial for a space experiment to ensure short integration time
- Modulation of the signal by rotation allows also reduction of thermal noise



Rotating torsion balances are operated at thermal noise level and demonstrate that it is reduced by rotation (Adelberget at al. 2009), but they are limited to rotation rates below the natural frequency, in order not to attenuate the expected signal

The GG experiment is unique in that it allows rotation rates well above the natural frequency (without signal attenuation…), hence a much stronger reduction of thermal noise, yielding a much shorter integration time

Abatement of thermal noise and integration time in GG



In the non rotating frame the force of the signal has low frequency:

$$(a_{th})|_{t_{int}} \simeq \sqrt{\frac{4KT\omega_n\phi(\omega_s)}{\mu}}\frac{1}{\sqrt{(\omega_s/\omega_n)}}\frac{1}{\sqrt{t_{int}}}$$

$$\omega_s \gg \omega_n$$

In GG (10^{-17} target in EP test, 10^{-17}g to be measured, 1Hz spin rate):

$$\omega_s/\omega_n \simeq 540 \quad \phi(\omega_s) \simeq 1/20000 \;\; m = 10\text{kg} \;\; T = 300\text{K}$$

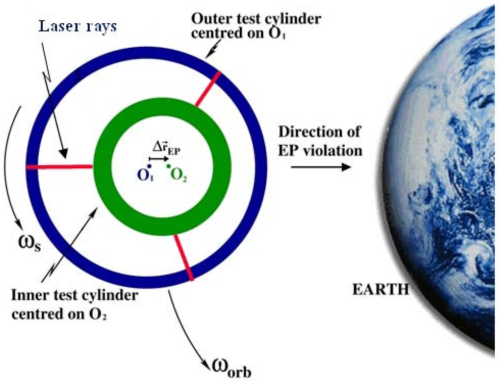
Integration time for 10^{-17} EP sensitivity and SNR=2: ~ 38 minutes!!!!

Damping noise from residual pressure is of the same order, noise force doubles, integration time grows by factor 4: ~ 2.5 hr total!!!

Macroscopic test masses weakly coupled and rapidly rotating drastically abate thermal noise!!!

[Pegna et al., in collaboration with JPL, submitted to PRL, 2011]

GG: Why laser metrology from JPL to replace main capacitance sensors?



GG has very low thermal noise and can detect an EP violation to 10^{-17} in 1 and half our. To exploit that that it needs a read out which:

- has extremely low noise
- is very sensitive to displacements in differential mode and almost insensitive to those in common mode
- disturbs the test masses (and affects their assembly) as little as possible

Laser metrology is the answer:

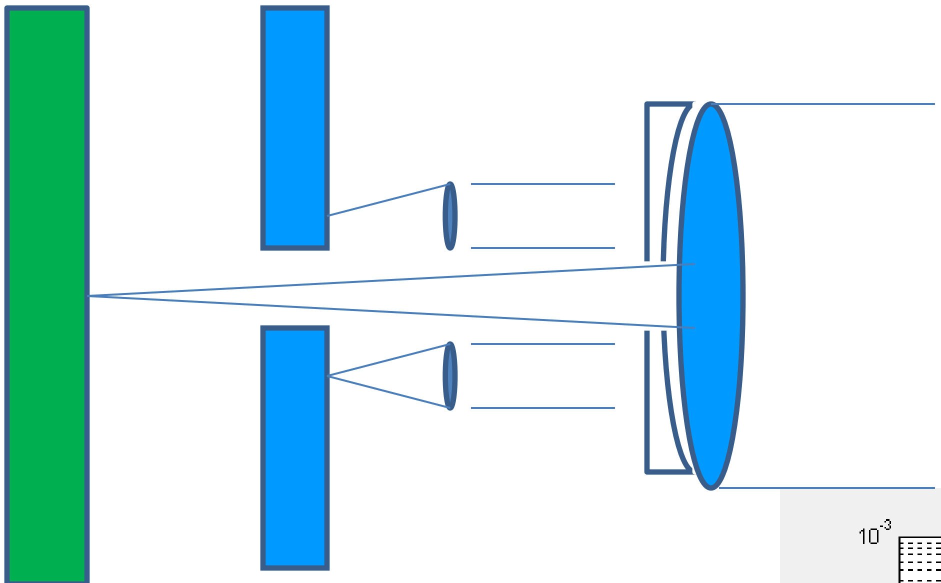
- It is far more sensitive than cap sensors
- Laser metrology is liner, hence large common mode motions do not give rise to false signals when two measurements are subtracted.
- Only light is deposited on the test masses (for the rest, they are totally "undisturbed" by the experimentalist during measurements …)

…+ allows larger gaps between the test masses (cap sensors would loose sensitivity), hence effects of electric charge patches are highly reduced and it is easier to get rid of them – larger gaps reduce other disturbances too **(GG TMs still have capacitors & springs to manage experiment initialization after unlock)**

Basic concept of GG laser gauge

Inner test mass

Outer test mass



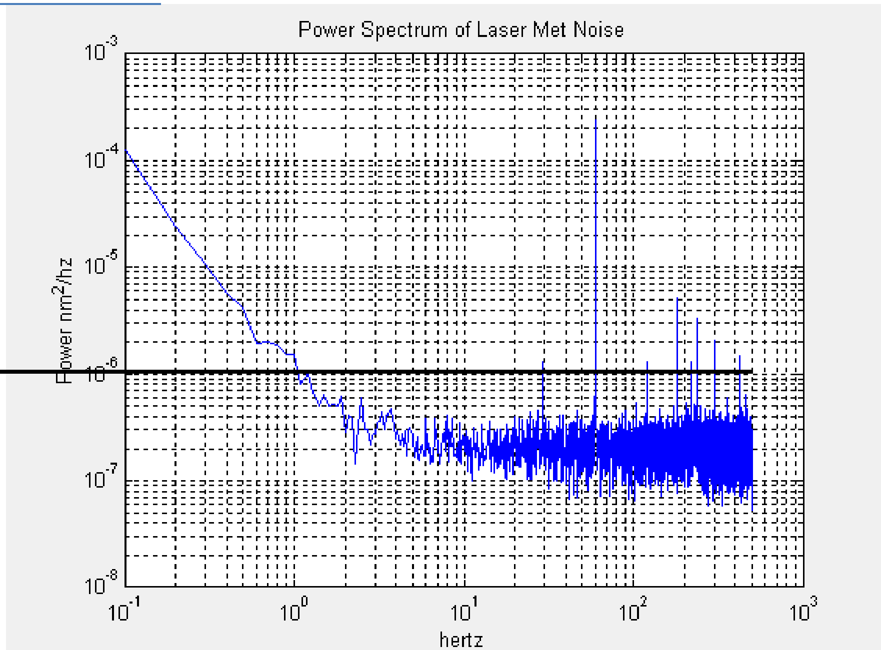
Positive lens focus
Light on inner mass

Negative lens with hole
Removes focus term
Smaller lenslets focus
light on outer testmass

Polished/coated surfaces

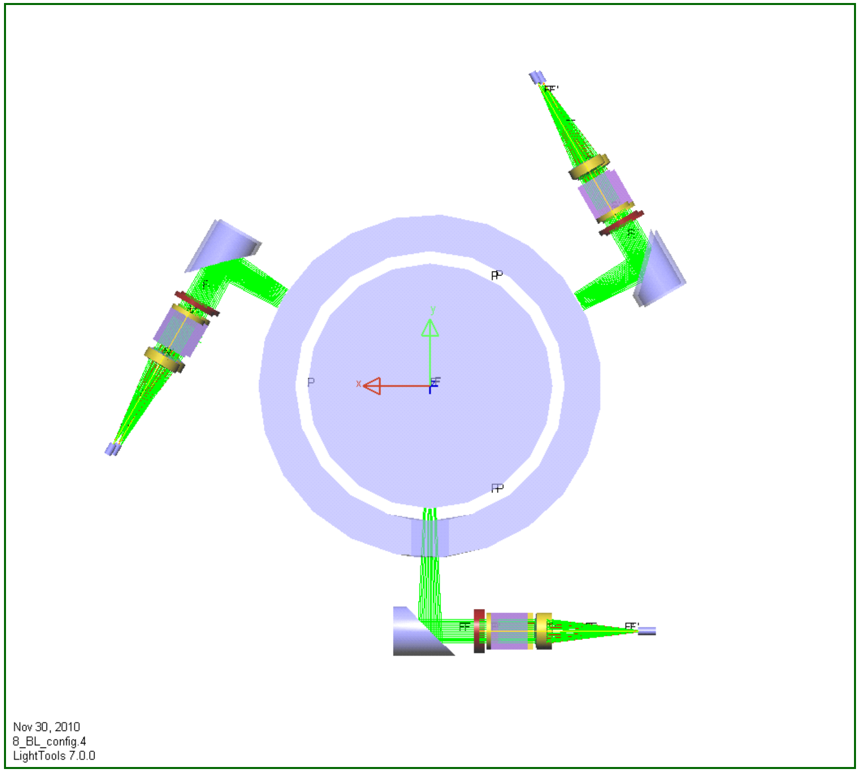
The sensitivity of the laser gauge is independent of the gap between the two test masses.

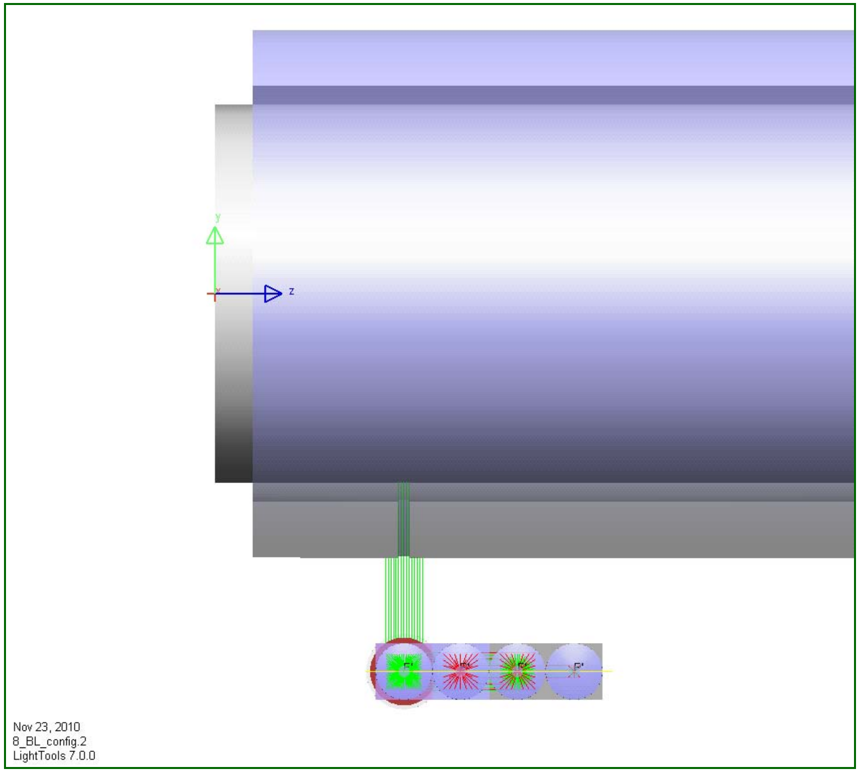
1 pico-m/rthz



GG laser gauge configuration concept (I)

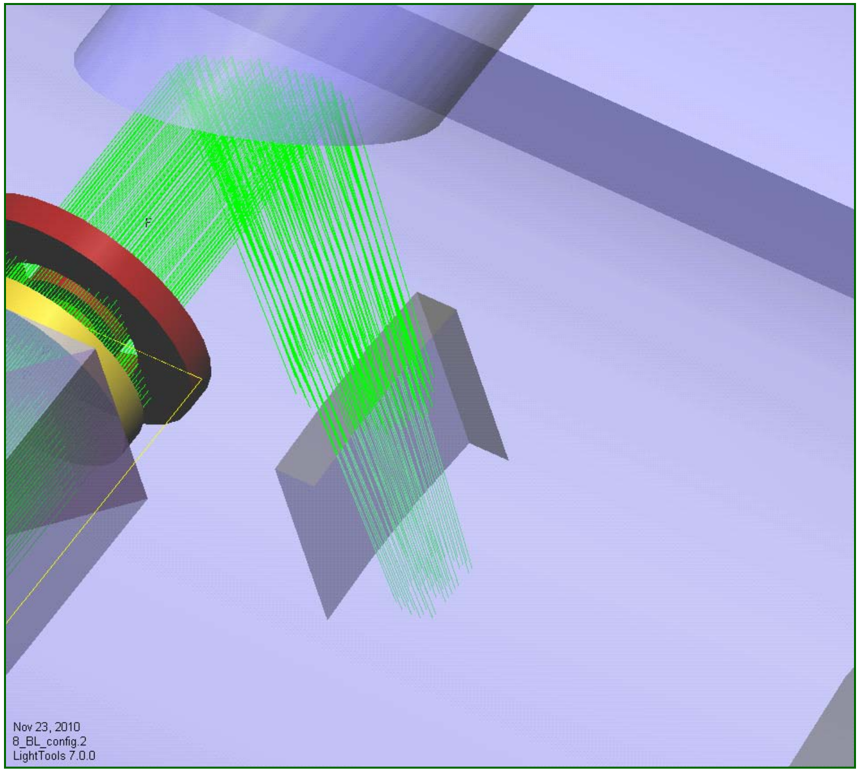
- Total six (6X) gauges, symmetrically distributed at two ends of the proof masses
- Provide 4 DOF measurement between inner and outer cylinders
- Partial redundancy

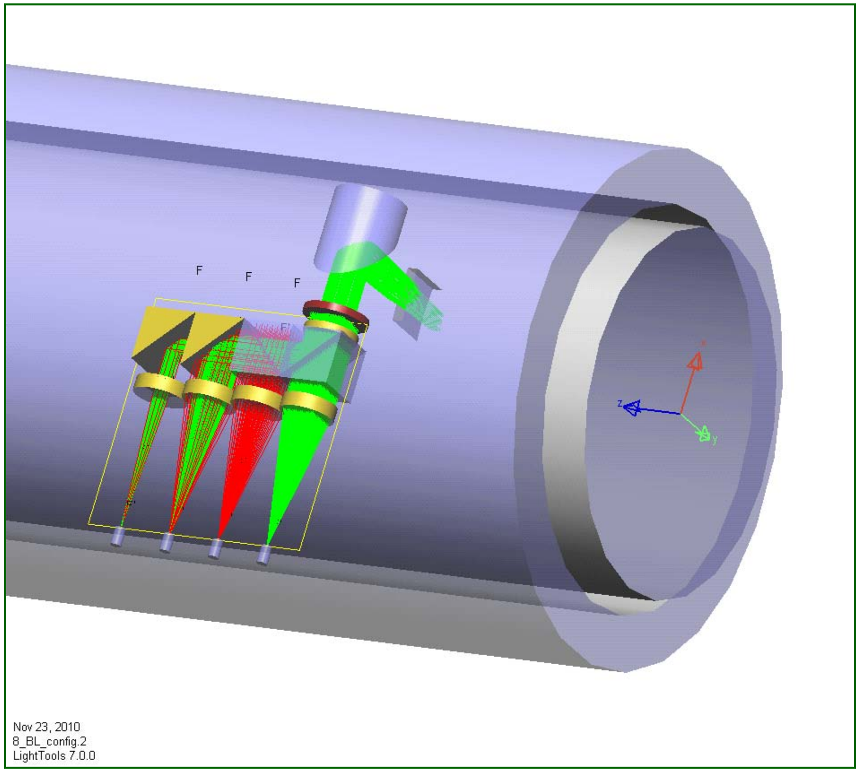




GG laser gauge configuration concept (II)

- Spatial split, between inner and outer cylinders.
- Outer cylinder has slot/holes
- Reflective patches on both inner and outer cylinders
- Heritage: SIM, PDAS, etc.





GG: Performing signal null checks with no additional accelerometer on board

If GG meets its target sensitivity and measures a non zero signal, is it possible to prove that it is EP violation (new force of Nature) and not a disturbance accountable with known Physics?

With very small thermal noise + laser metrology, the answer is yes:

- With 2.5 hr integration time for SNR=2, GG can make a full measurement to 10^{-17} in 1d (15 orbits)
- GG has extremely high spin energy and its axis (normal to the sensitive plane) is fixed in inertial space during the mission
- Instead, being in sun-synchronous orbit the normal to the orbit precesses around the Earth axis by 1^{o} per day, so the angle ϑ between the spin axis and the orbit normal changes daily. With no attitude control GG can have $-40^{o}<\vartheta<+40^{o}$ in 80 days, with an EP measurement each day….

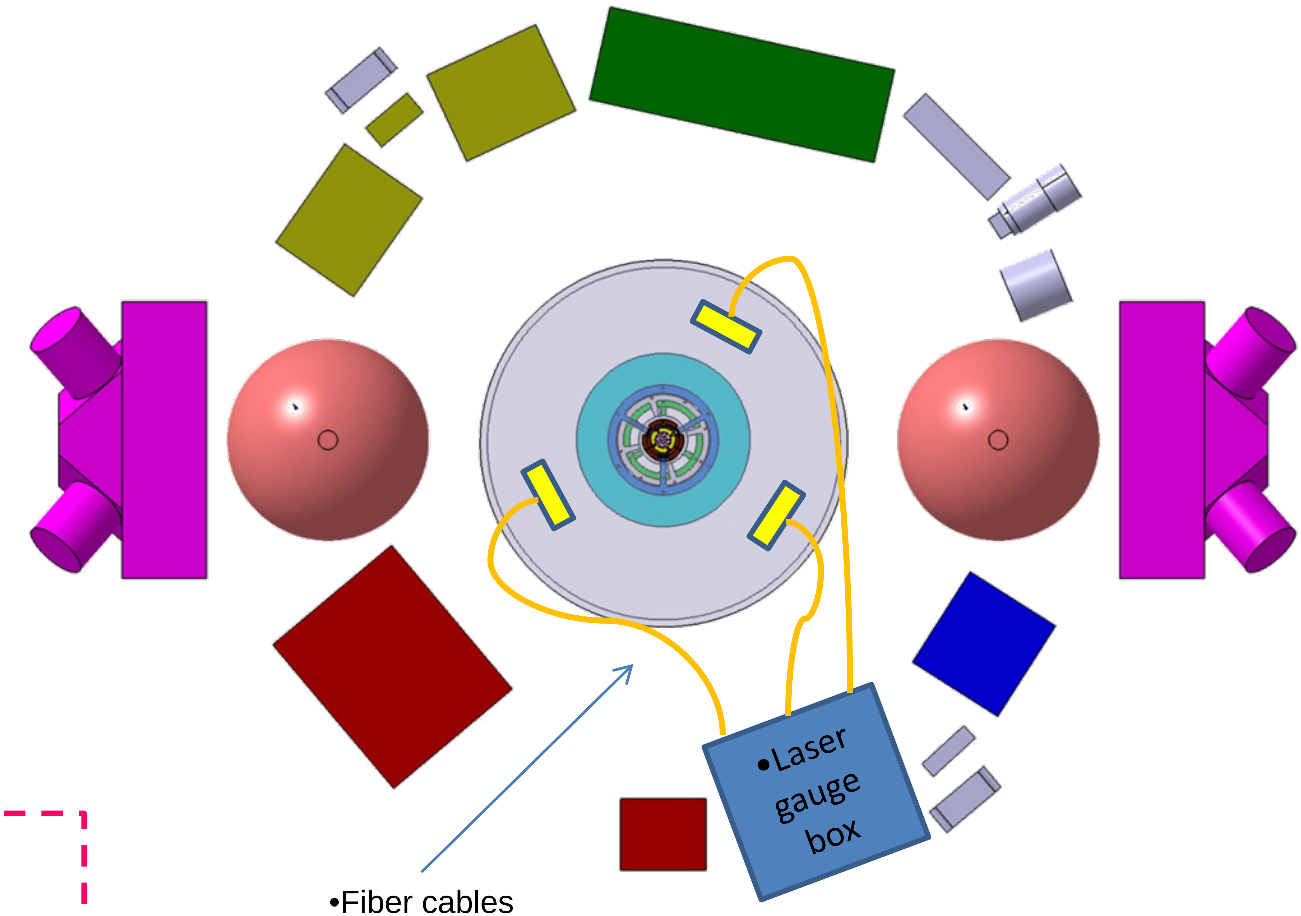
EP violation signal and the most dangerous disturbances which need to be distinguished from it have their own specific signature as function of ϑ, which allows them to be very clearly distinguished……

[Nobili et al., in press]

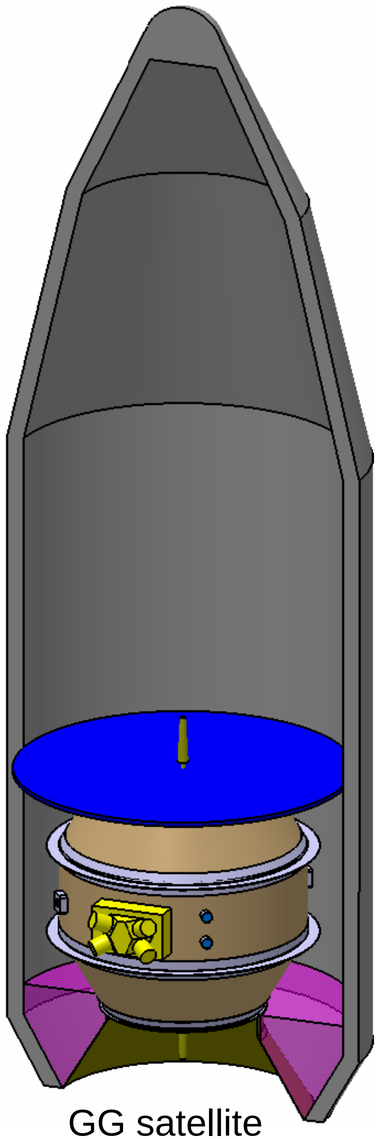
What is around the test masses: top view

- FEEP Propulsion
- Nitrogen Propulsion
- P/L Equipment
- AOCS
- Power
- Communications
- Data handling

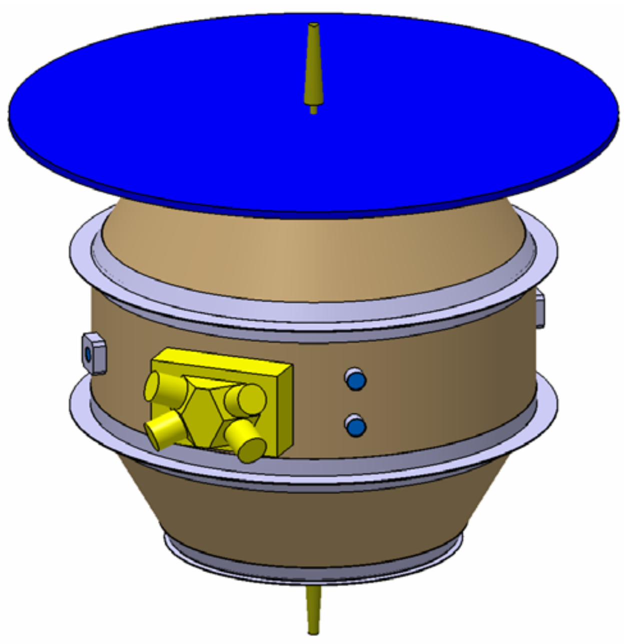
- **•Laser gauge box**
- **•Beam launchers** **(6X)**



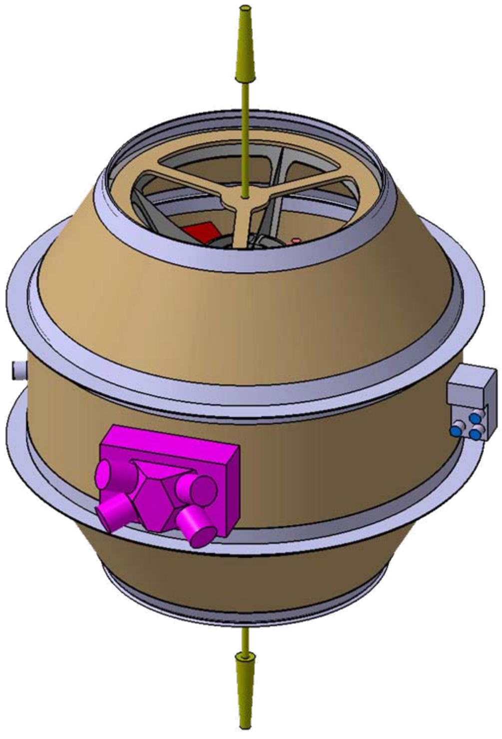
The GG satellite



GG satellite inside Taurus fairing



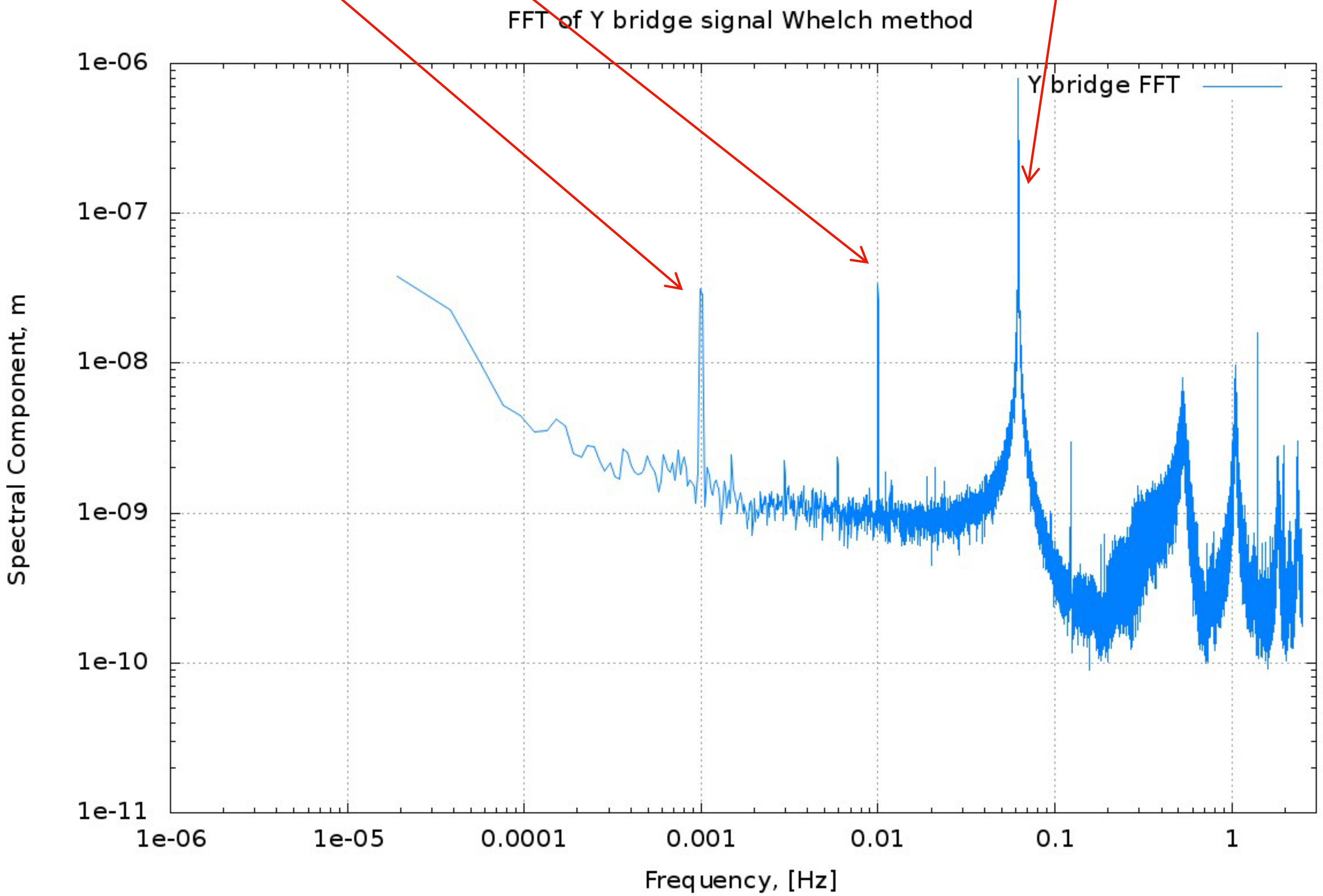
GG satellite



GG satellite without solar panel

GGG: Evidence that signals above resonance are not attenuated (I)

GGG not rotating: 2 force signals of same amplitude applied in the lab frame at frequencies 0.001 Hz and 0.01 Hz), below the natural frequency 0.06 Hz



GGG: Evidence that signals above resonance are not attenuated (II)

GGG spinning at 0.19 Hz with natural frequency 0.1 Hz : same signals applied at 0.01 Hz and 0.001 Hz in the lab frame.

Because of the lower natural frequency they should both produce smaller effects by the ratio of the natural frequencies squared: $(0.1/0.06)^2=2.78$

Because of rotation they are upconverted above the natural frequency, and in typical 1D forced oscillators they would be attenuate another factor.

So, we should see a total attenuation by a factor 8, which we do not see in GGG

(we see only the expected factor 2.78)

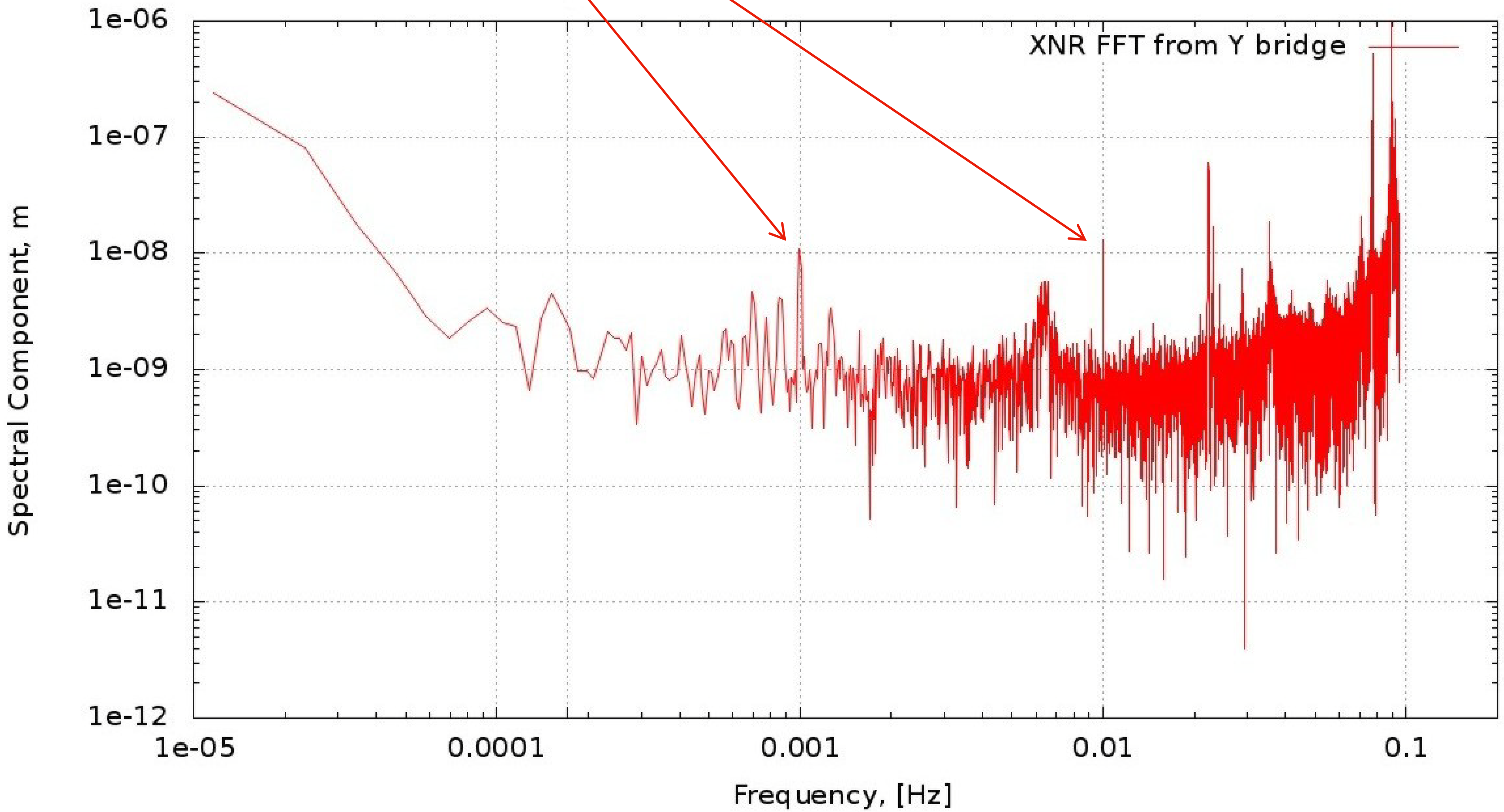
NOTE: in space the advantage is much bigger because it is possible to spin much faster than the natural frequency with no attenuation of the target EP violation signal!!

[Pegna, Nobili et al., to be submitted to PRD]

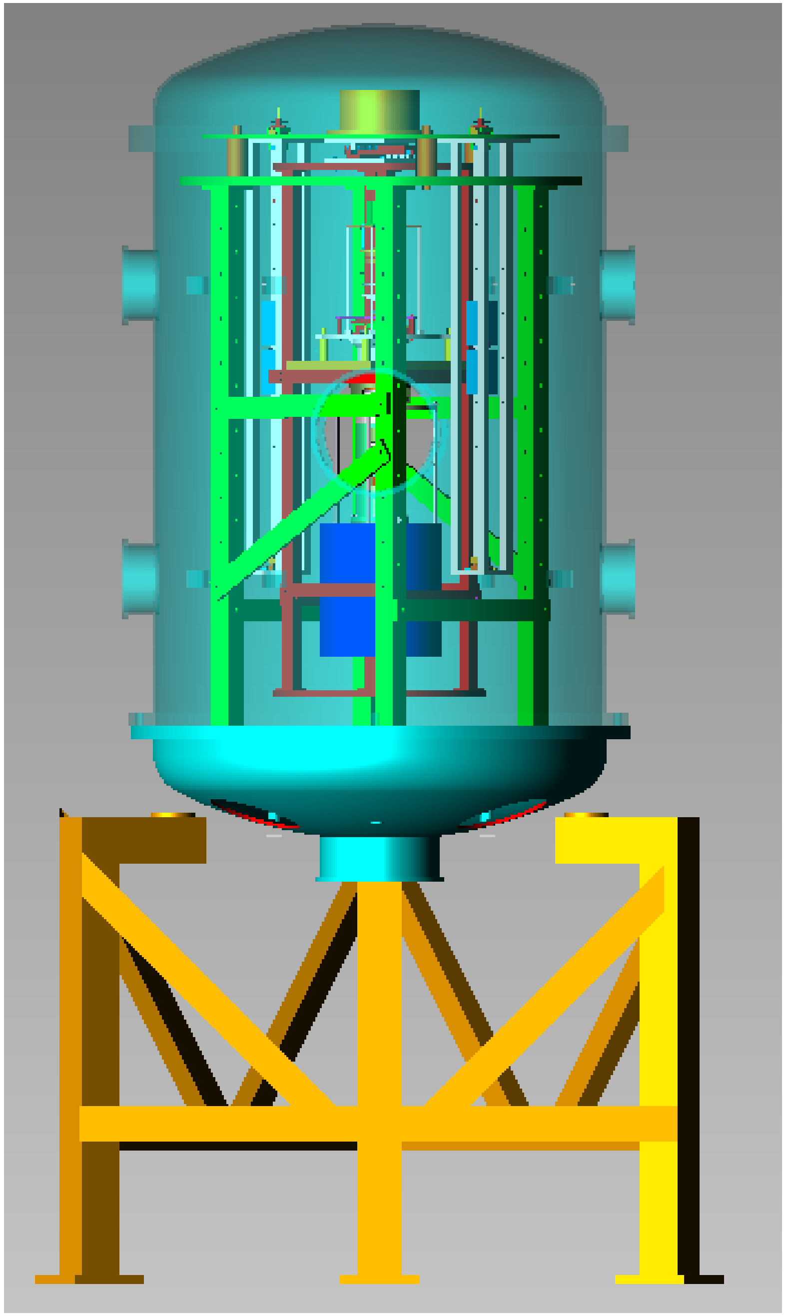
GGG: Evidence that signals above resonance are not attenuated (III)

We see only the factor almost 3 reduction expected by the slightly higher natural frequency, certainly not a factor of 8!!!

GG/GGG has the unique property that a low frequency signal can be modulated above the natural frequency (with great advantages) without being attenuated!

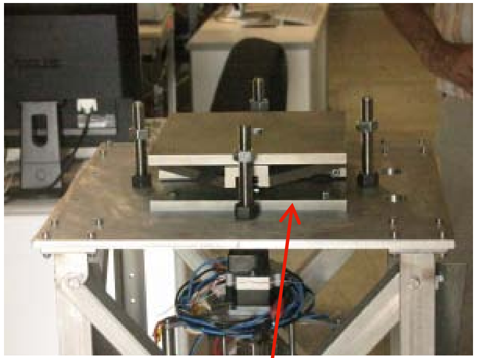


sGGG (ASI funding) (I)



sGGG (II)

sGGG (III)

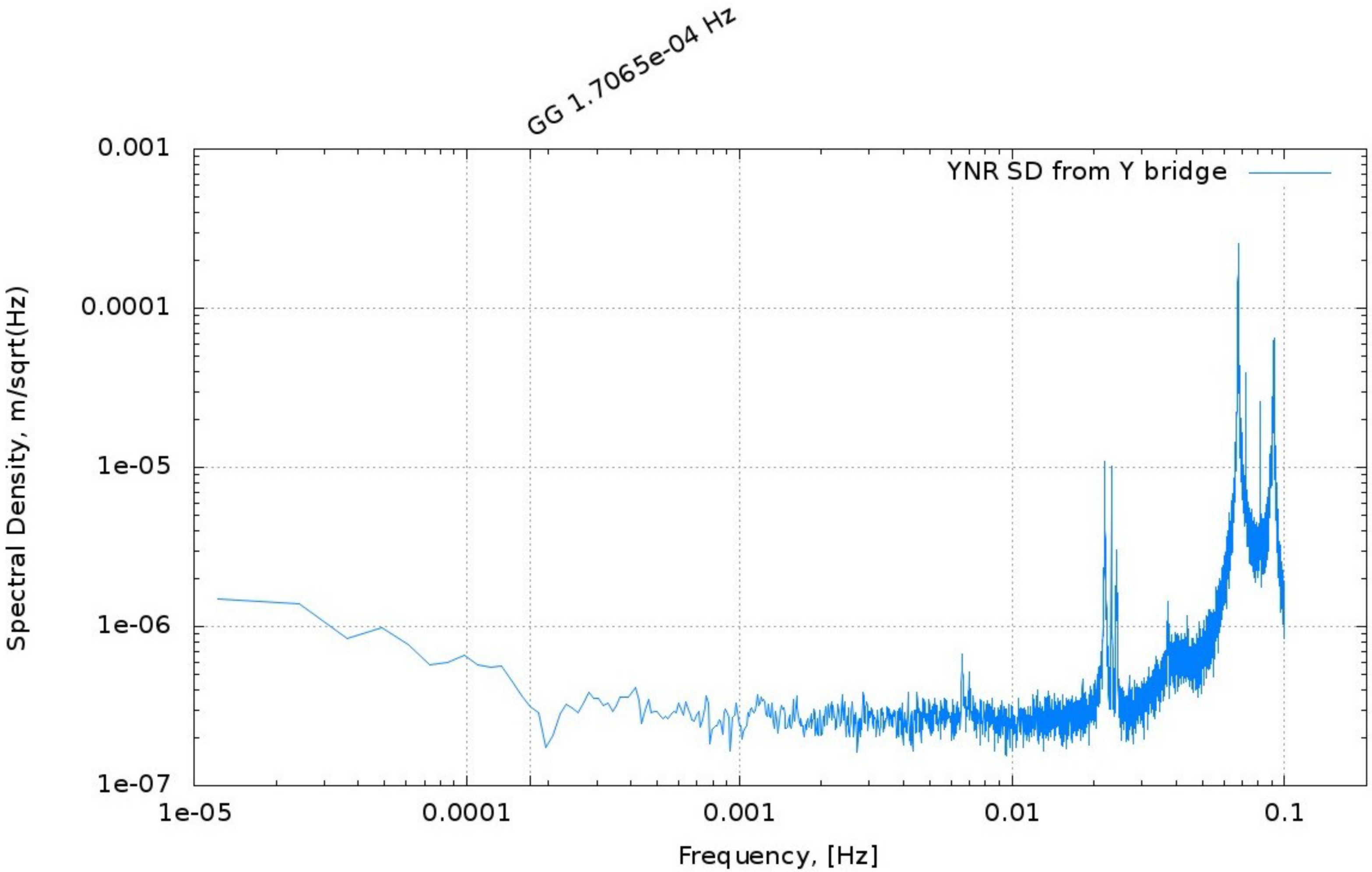


2D laminar suspension (not rotating)

First run of sGGG (end 2010)

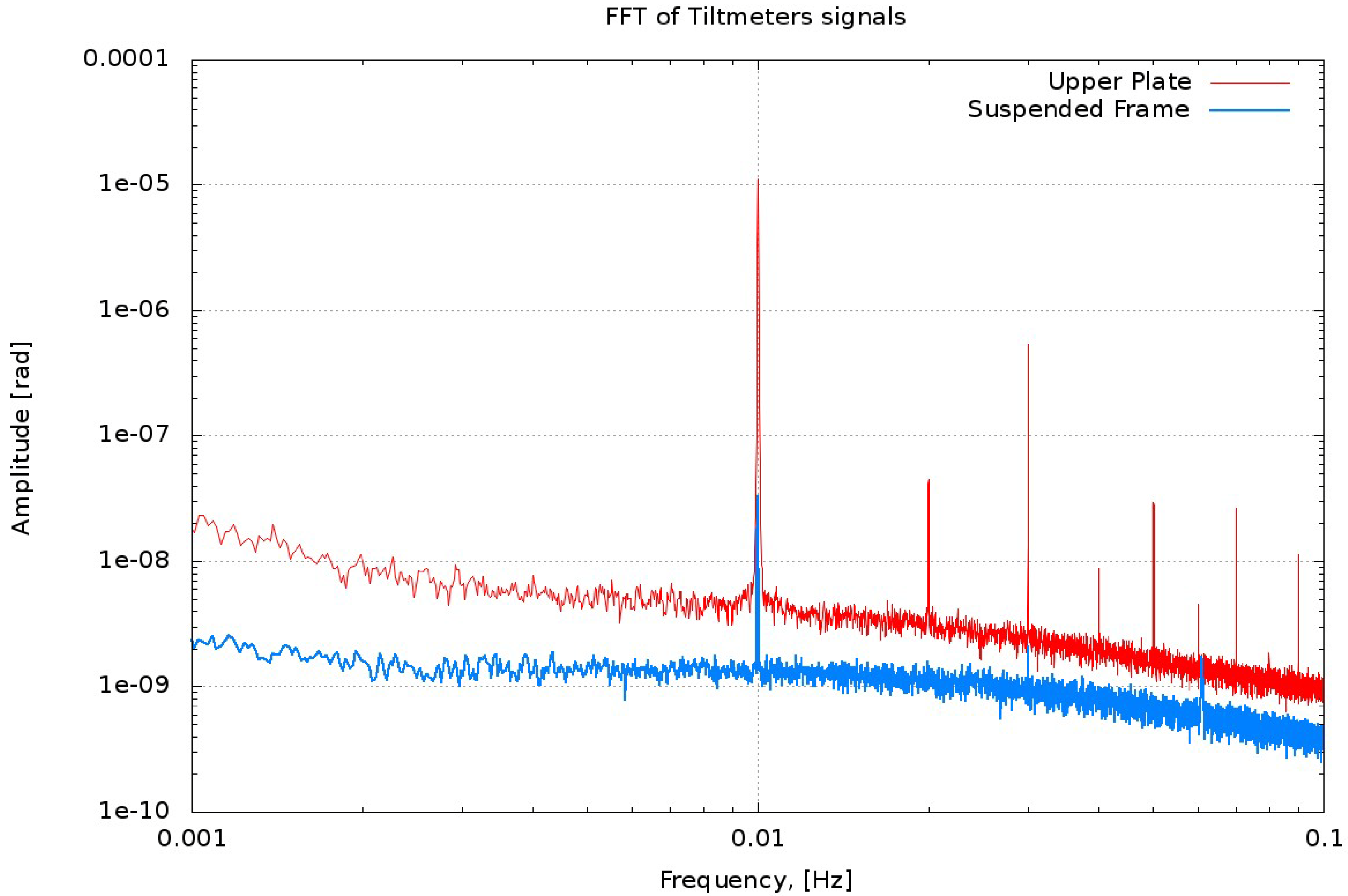
Factor 10 improvement from non-suspended system + spectrum much more flat at low frequencies (passive tilt attenuation much better than active tilt control)

@ GG orbital frequency: 3e-7 m/√Hz (in 1 week, sensitivity to Δa=5e-11 g)



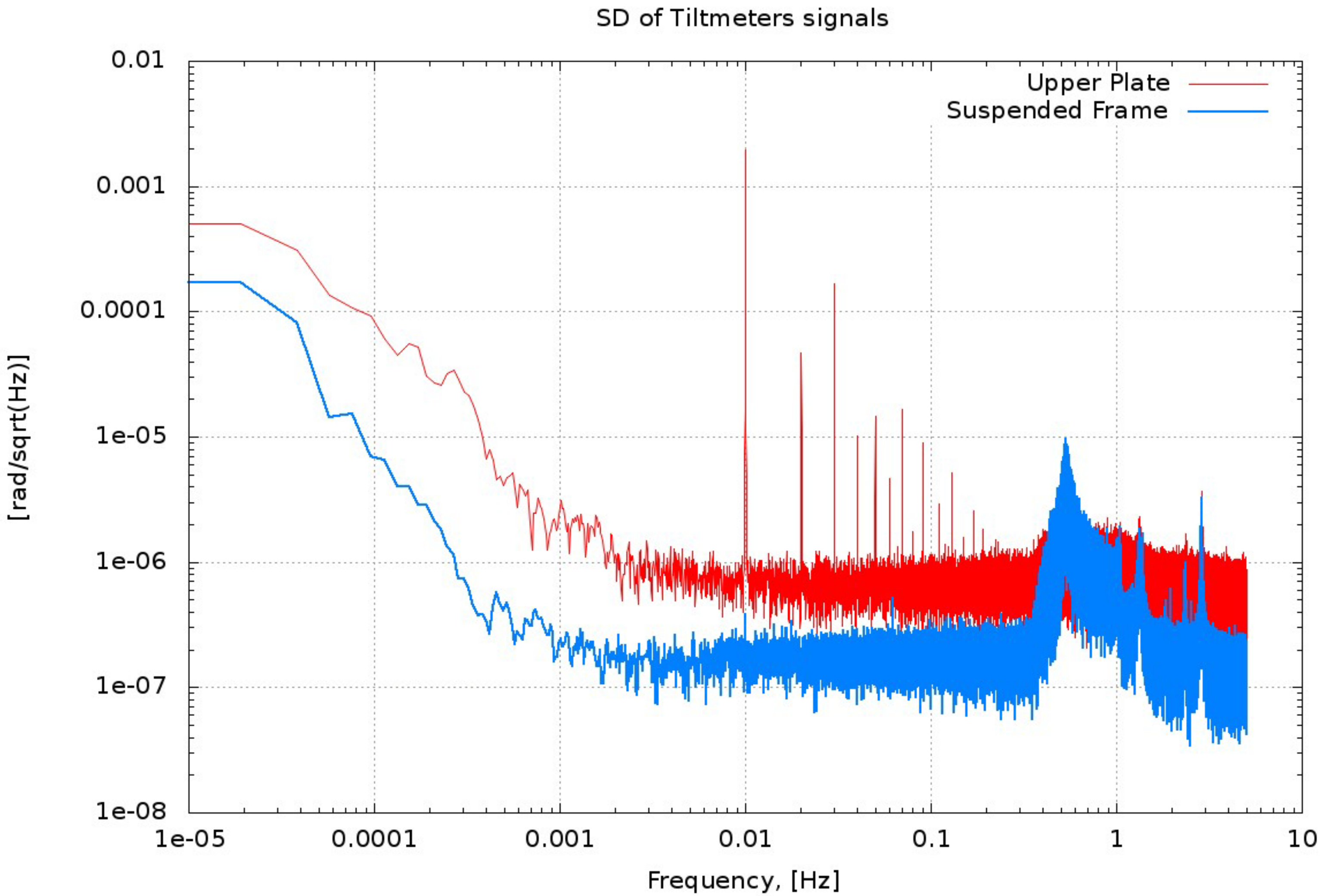
Tilt attenuation by 2D laminar suspension (I)

Attenuation factor 300 measured by applying strong tilt to the frame rigid with the chamber , zero spin (.. limited by cables connecting fixed to suspended frame)



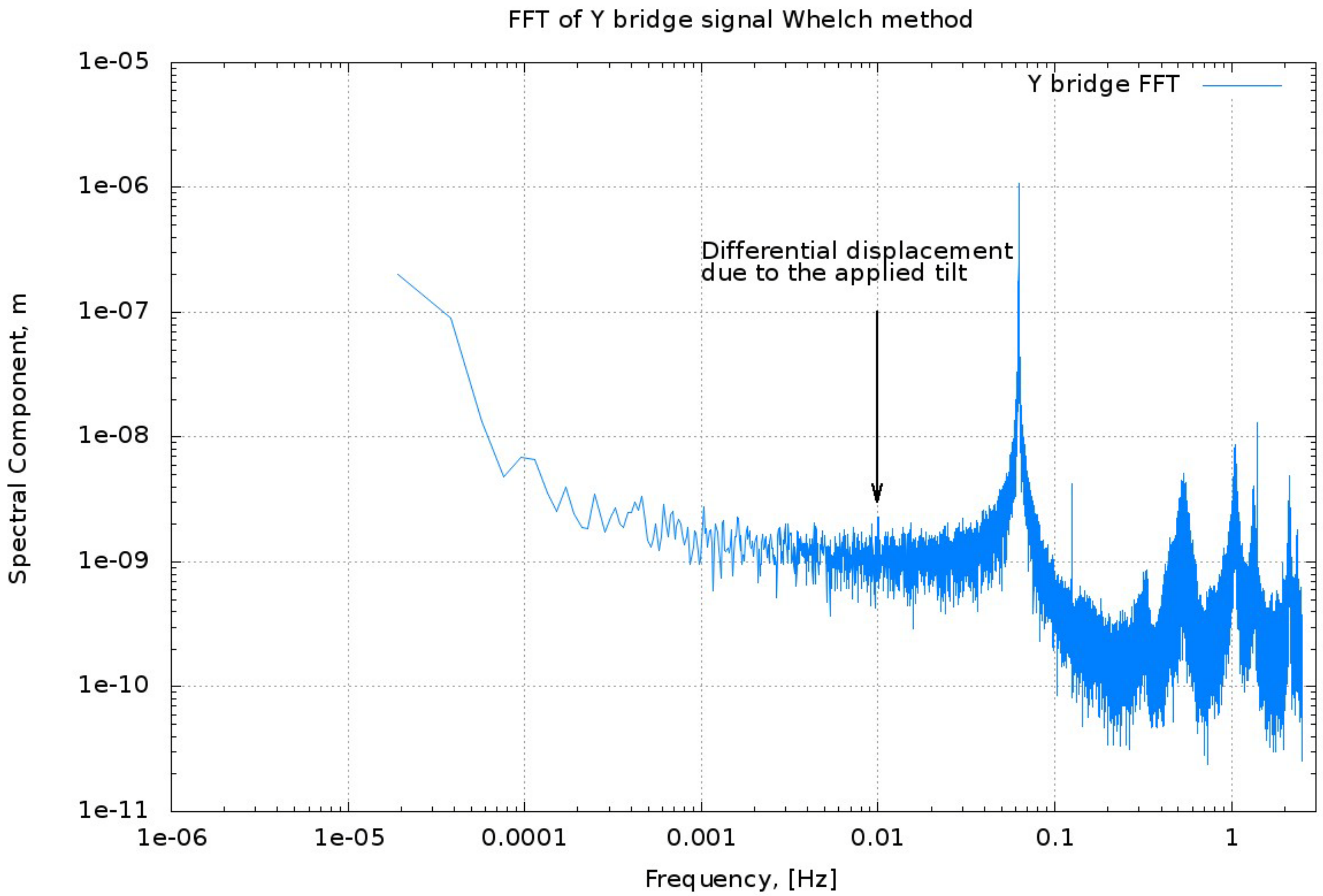
Tilt attenuation by 2D laminar suspension (II)

Attenuation factor **5000** measured after using thin cables



Tilt attenuation by 2D laminar suspension (III)

After attenuation by factor 5000 the effect of the applied tilt is visible as a relative displacement of the test masses just above noise



sGGG simulator under training

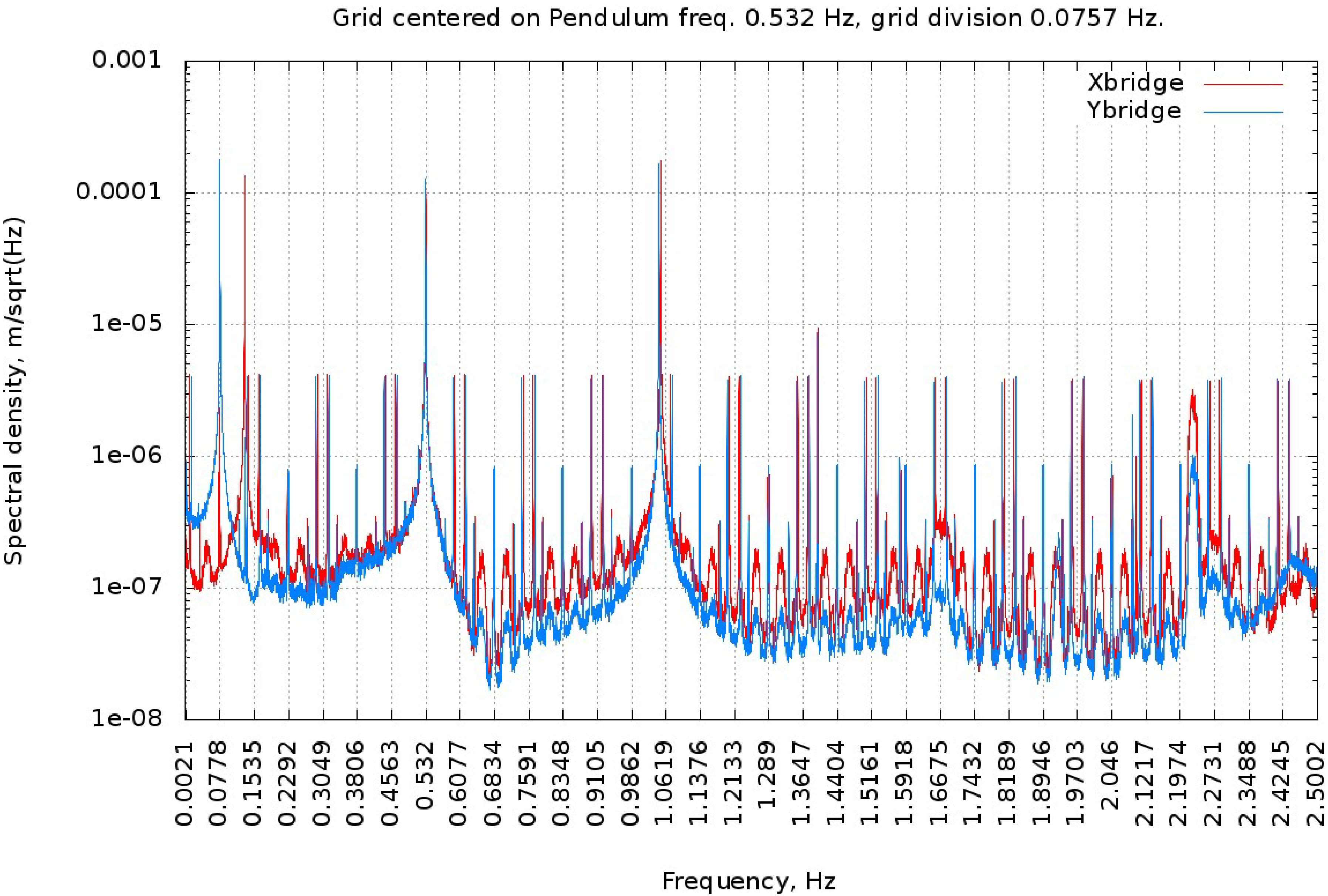
A simulator of sGGG has been set-up, based on the engineering construction drawings of the system. It is written in SimMechanics

The non rigid components of the system are implemented by forcing the simulator to match the measurements.

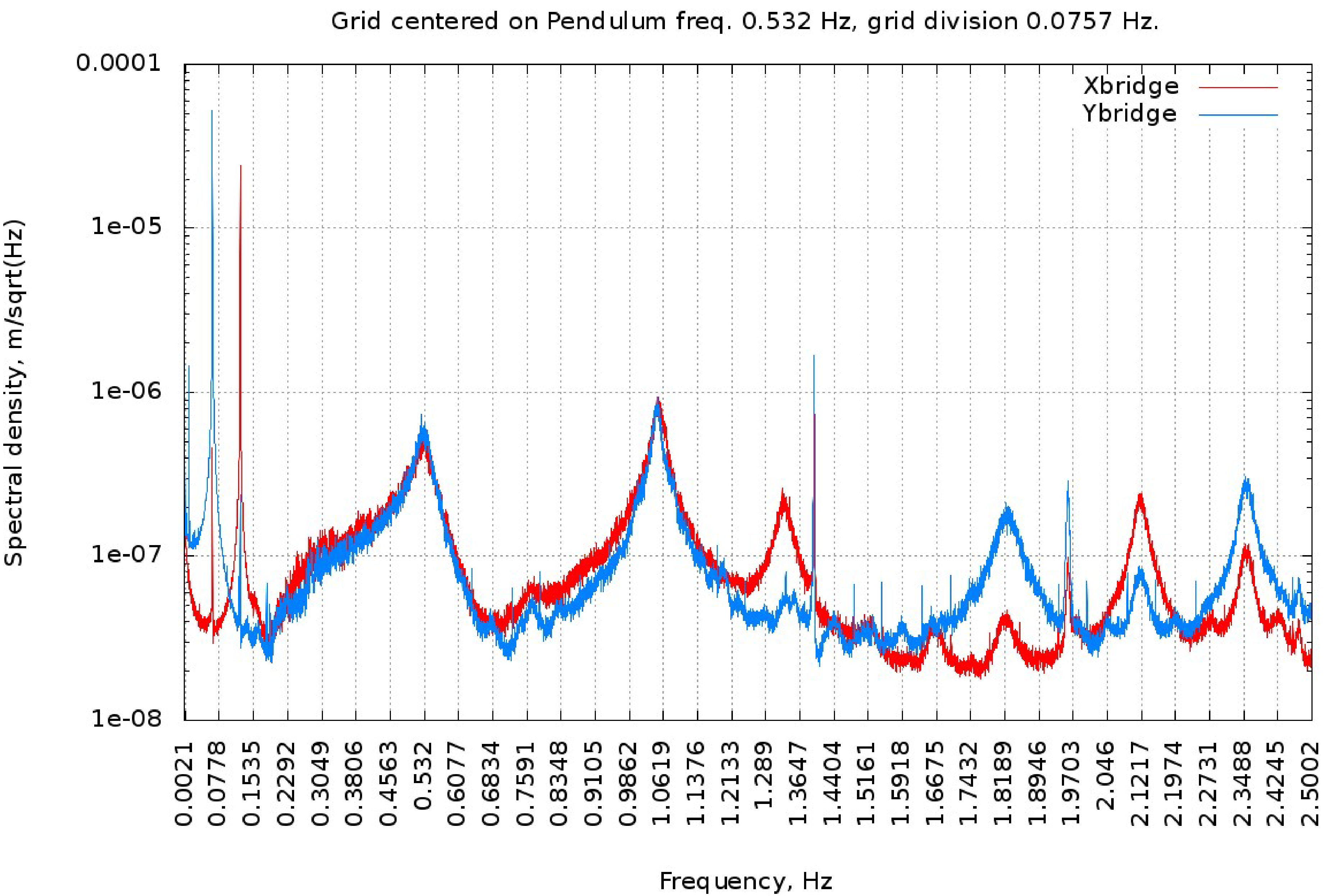
- it does reproduce all the natural frequencies
- It does reproduce the observed tilt attenuation factor

It can be used to infer effects which are hard to measure (e.g. effects of horizontal accelerations) or to check the effects of hardware changes in order to establish if they are worth implementing

Reducing energy coming from the pendulum motion of the suspended frame (I)

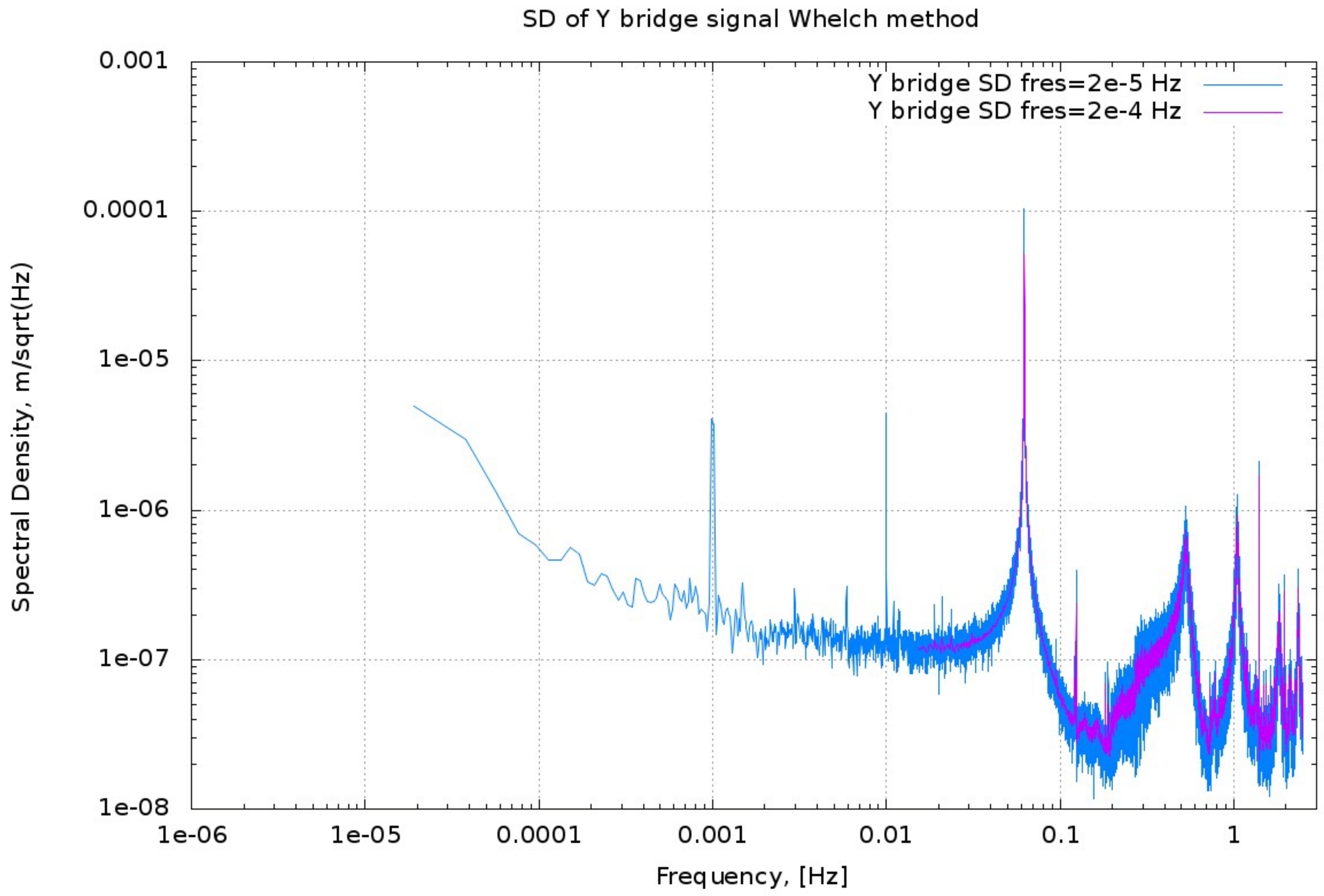


Reducing energy coming from the pendulum motion of the suspended frame (II)



Read-out electronic noise and advantage of spin

At 0.2 Hz spin rate electronic noise is much small than at the low frequency of interest (1.7e-4 Hz) not the limiting noise (by about 1 order of magnitude) – new electronics is under construction



Hunting low frequency (1.7e-4 Hz) noise sources

- Horizontal seismic accelerations: under study with simulator: most probably not yet a limitation but common mode effects may be larger
- Uniformity of rotation: demultiplied stepper motor under testing
- Rigidity of connection from rotor to laminar suspension (can have low frequency changes if not rigid enough; current frame questioned)
- Ball bearings: dust or small defects of balls may produce low frequency motion of shaft (may be the main culprit) .. Move to magnetic bearings…
- Small leakage from vacuum chamber (gives rise to low frequency disturbance): simple test proposed by Erseo Polacco will be done soon

Another factor 10 improvement not too far away

But to reach 10^{-15} g sensitivity we are heading towards a smaller rotor (test cylinder 1 kg each: weaker coupling, higher acceleration sensitivity) with optical read out (from JPL, though not the laser gauge to be used for GG in space; low noise and differential) and low noise motor and bearings .

Persone-Pisa

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Richieste alla Sezione: 2 settimane uomo di Andrea Basti per passaggio e controllo di disegni fatti da lui o ai quali ha contribuito alla ditta esterna che paghiamo per fare i disegni costruttivi di cui abbiamo bisogno

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