Gravitational Reference Sensor: progress for LTP and LISA

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OUTLINE

Introduction

GRS IMPLEMENTATION

Engineering Model for LTP: fabrication status

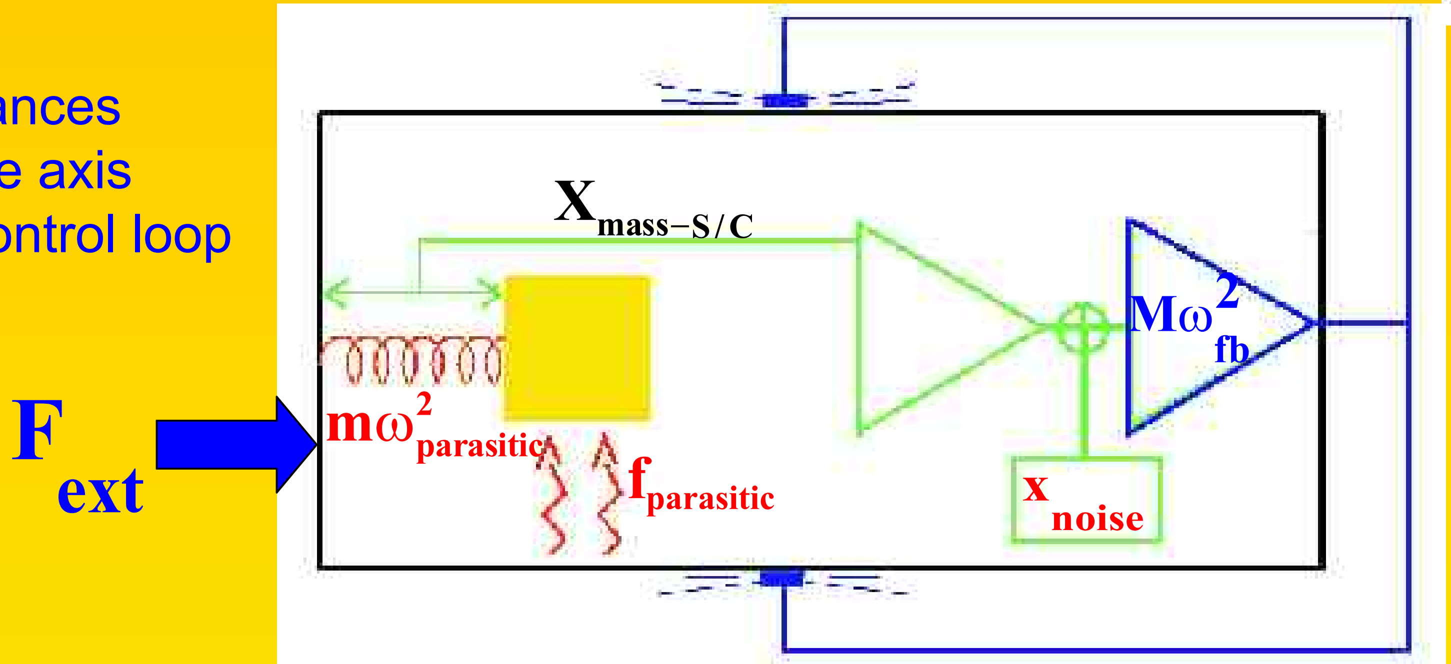
Back-up/upgrading alternatives
Investigation ongoing in Trento

GRS ON GROUND TESTING

Verification of the noise model:
status and prospective

On ground test facilities

Performances of a single axis "drag free" control loop



The residual acceleration of the test mass will be

$$a_{residual} \approx \omega^2{}_{parasitic}\left(x_{noise} + \frac{F_{ext}}{M_{S/C}\,\omega^2{}_{fb}} \right) + \frac{f_{parasitic}}{m}$$

S/C displacement wrt to test mass

⇨ Requirements for max PSD of $\mathbf{F_{ext}}$, $\mathbf{f_{parasitic}/m}$, $\mathbf{x_{noise}}$ and for ω_{int} and ω_{fb}

Contribution from: S/C, LTP, Gravitational Sensor (CM, CMS, GSC)

Requirements of GRS for LISA

$$a_{residual} \approx \omega^2_{parasitic}\left(x_{noise} + \frac{F_{ext}}{M_{S/C}\,\omega^2_{fb}}\right) + \frac{f_{parasitic}}{m}$$

Force noise

$$S^{1/2}_{\frac{f_{int}}{m}} \le 2.8\times10^{-15}\left[1+\left(\frac{f}{3\,\mathrm{mHz}}\right)^2\right]\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}} \quad \text{for } 0.1\,\mathrm{mHz} \le f \le 0.1\,\mathrm{Hz}$$

Stiffness

$$\left|\omega_p^2\right| \le 4\times10^{-7}\left[1+\left(\frac{f}{3\,\mathrm{mHz}}\right)^2\right]\frac{1}{\mathrm{s}^2} \quad \text{for } 0.1\,\mathrm{mHz} \le f \le 0.1\,\mathrm{Hz}$$

Displacement noise

$$S^{1/2}_{x_n} \le 1.75\times10^{-9}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \quad \text{for } 0.1\,\mathrm{mHz} \le f \le 0.1\,\mathrm{Hz}$$

Noise Model as Design driver for the GRS

Identifies main sources of
displacement noise
force noise
stiffness

Several required functionalities are also design driver and introduce additional noise sources

Measurement and Management of the TM charge
Actuation of some TM DOF (LTPand LISA are different)
Caging mechanism of the TM upon launch

↓

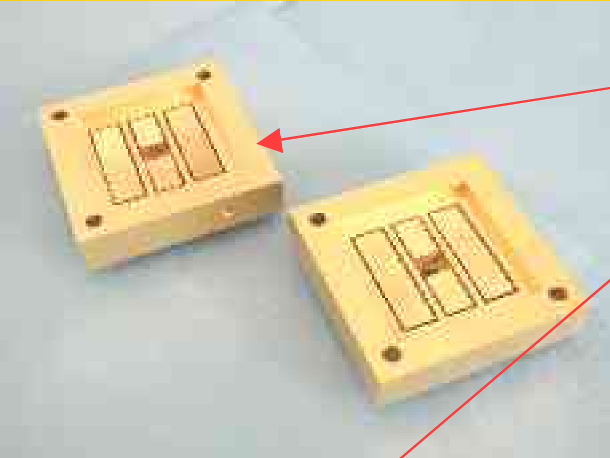
Design of position sensor bread-board prototypes
Design of the Engineering Model for LTP

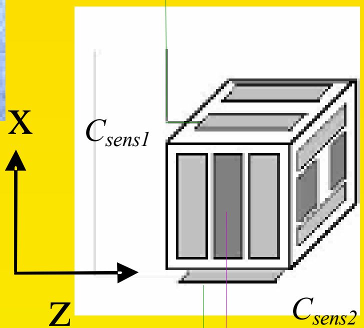
The displacement sensor in Trento

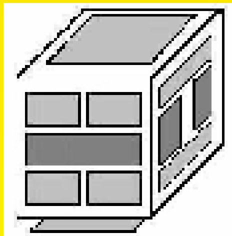
Breadboard prototypes

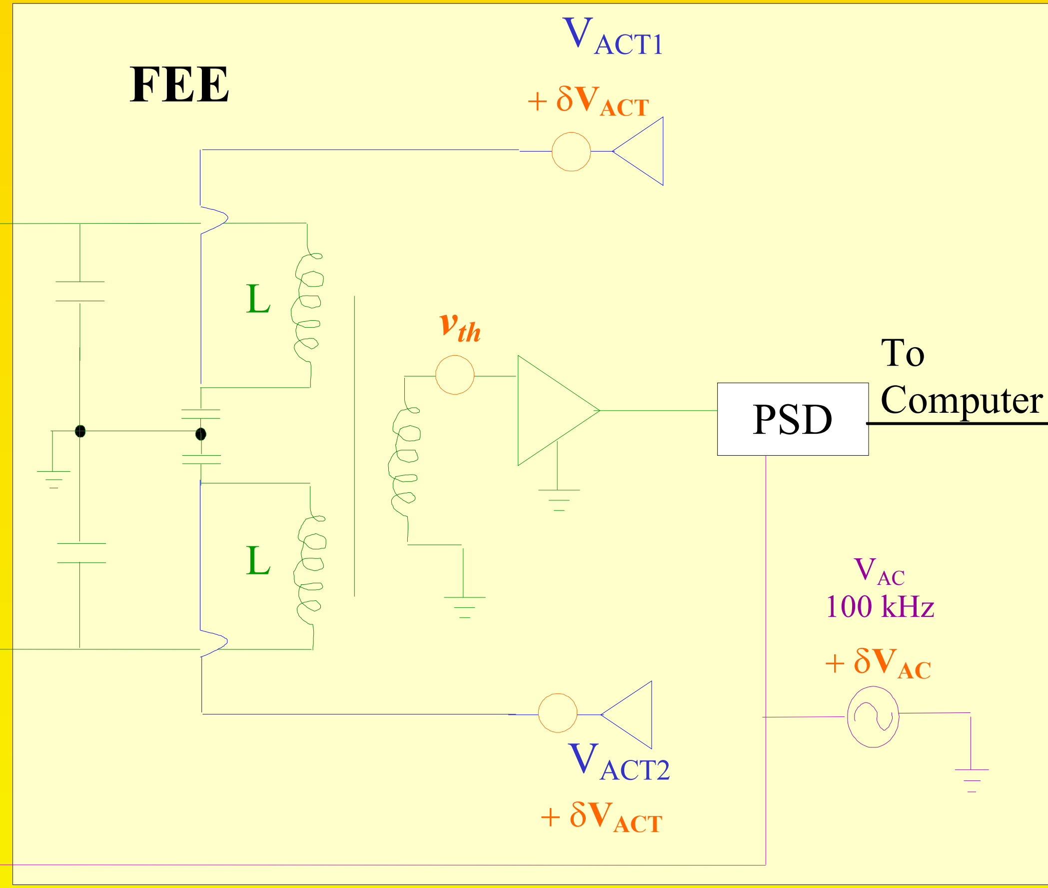
Metal ceramic composite structure

2 mm gap



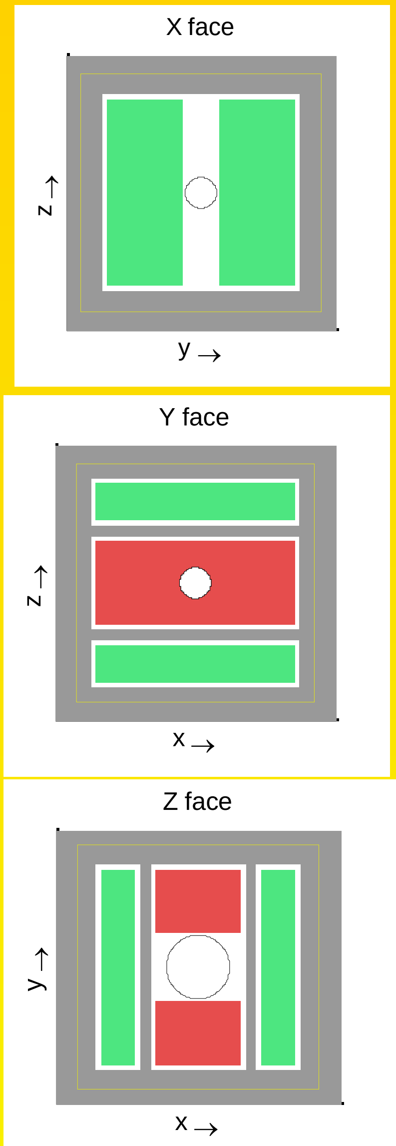


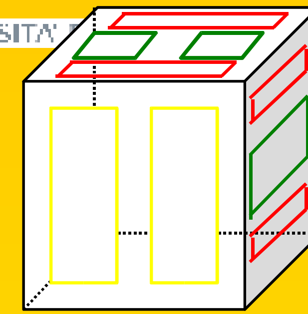




Engineering model prototype for LTP

Baseline Electrode Configuration





- All gap sensing, with relatively large gaps

  4 mm along x, 4 mm injection
  Baseline: YZ-Injection 2.9 y, 3.5 z

- Injection on two axes

  Reducing off-axis stiffness to reduce force cross talking

- 46 mm test mass

  ~ 2 kilos
  Sensor properties improve with size and mass

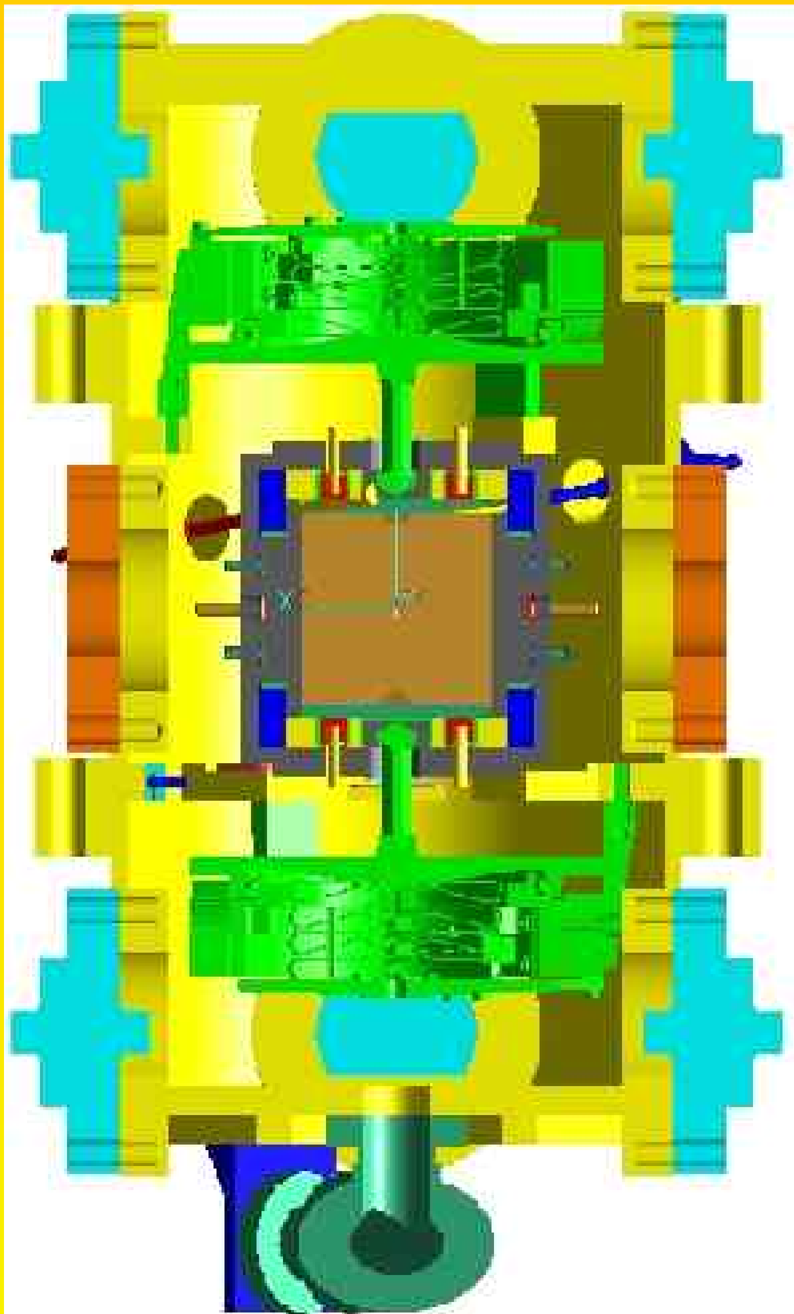
- Space for caging, split injection electrodes

  1-2 mm buffer between plunger / indentation and injection electrodes

Gap sensing
4 mm gaps
Molibdenum+SHAPAL (sapphire)

Engineering Model for LTP

- **GRAVITATIONAL SENSOR CORE (CGS)**
  - A free floating cubic, 27% Pt-73% Gold TM,2 kg
  - 6-DOF capacitive motion sensor
  - An electric field based TM actuation system
- **VACUUM ENCLOSURE (CGS)**
- **CHARGE MANAGEMENT SYSTEM (ICL):**
  - TM charge management control
  - UV light, photo electron extraction based,
- **CAGING MECHANISM (RAL)**
  - cages the mass via the action of a plunger that pushes it against end-stops
  - prevents both translation and rotation
  - allows multiple operation including re-caging
  - releases the TM form the centre of the housing
- **FEE:** sensing and actuation



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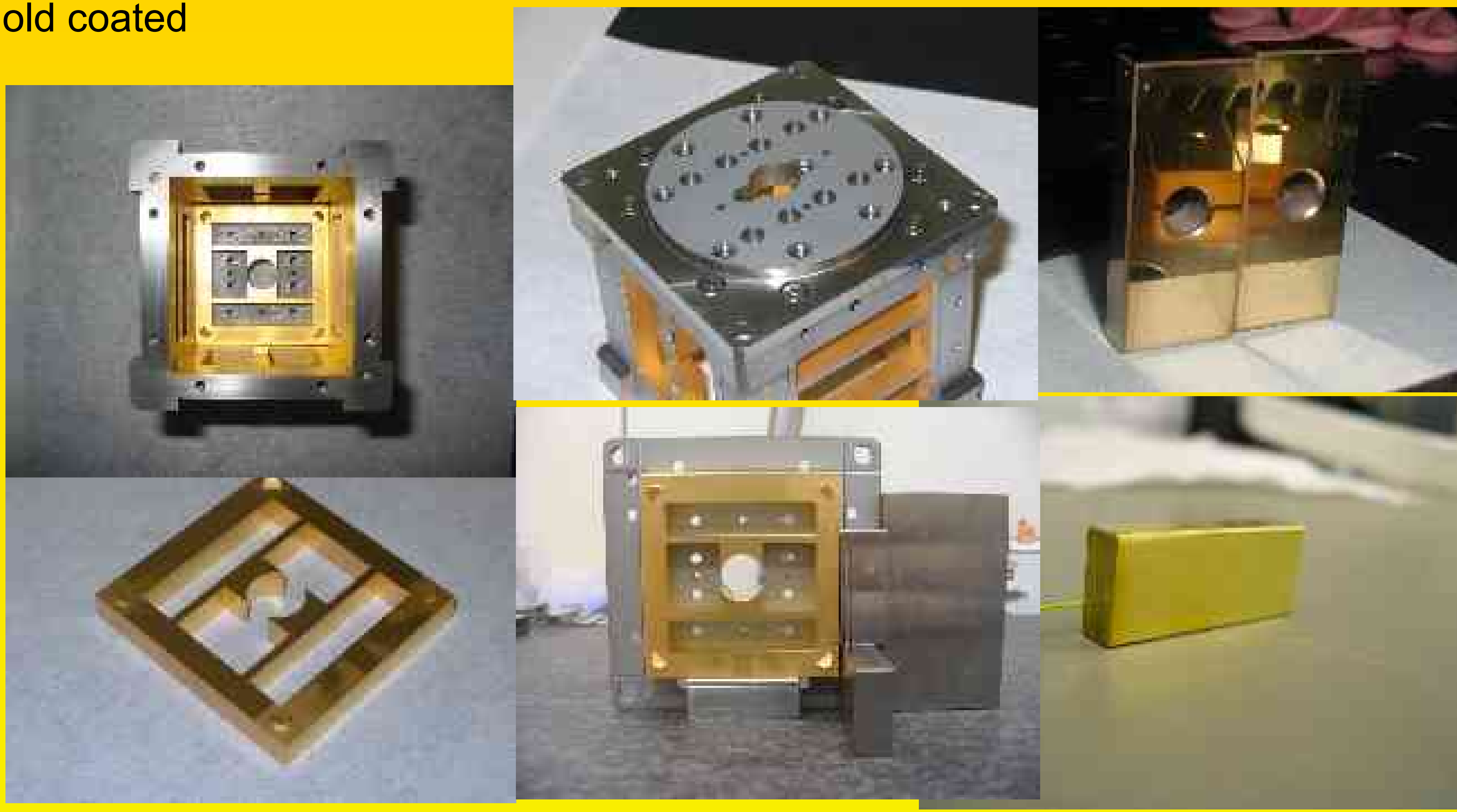
EM for LTP status

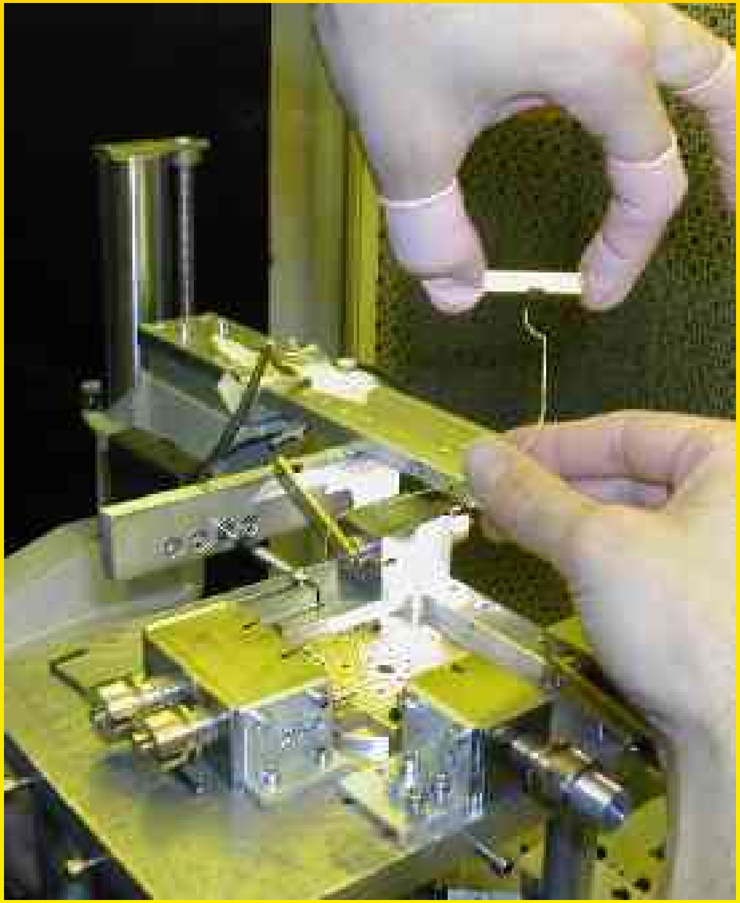
Manufacturing of Housing and Electrodes completed

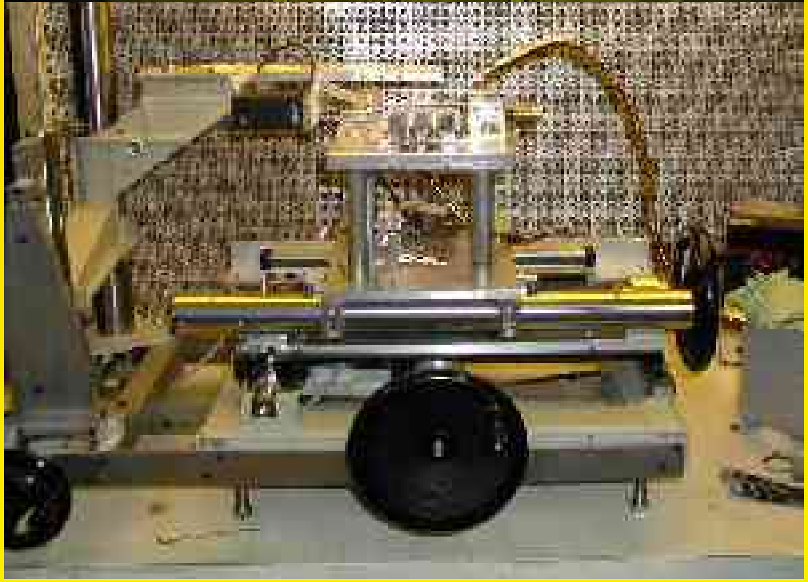
Molibdenum+ SHAPAL
Gold coated



EM for LTP status

Assembly of the EH on going



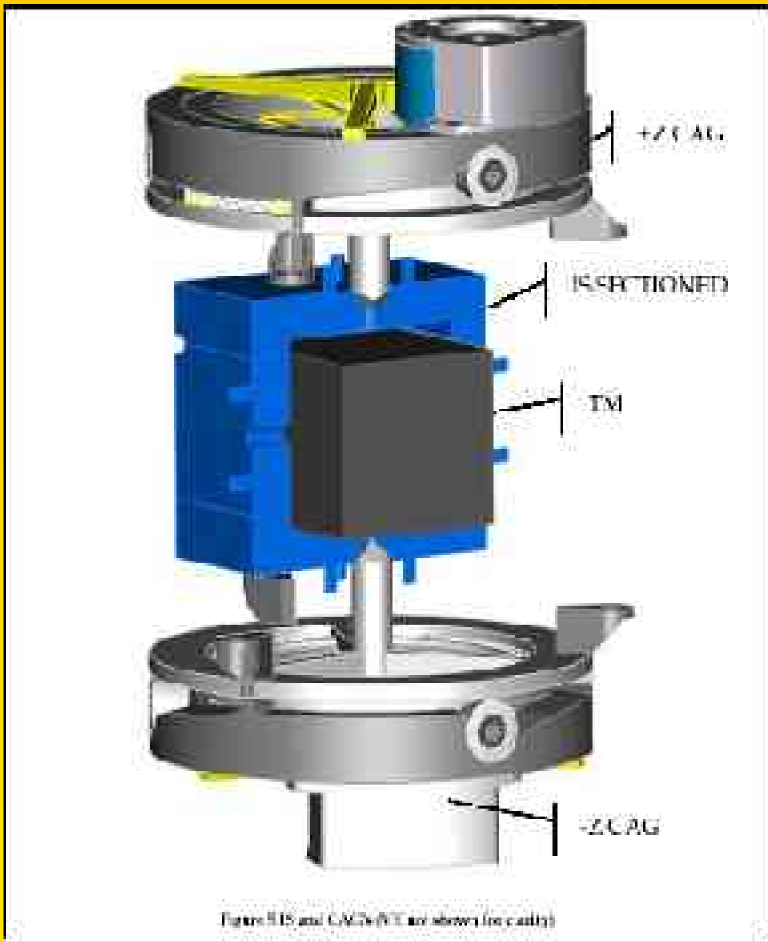


EM for LTP status

Test Mass: machining and characterisation completed

EM for LTP status
Caging Mechanism

Talk of Sam Tobin



Rutherford
Appleton
Laboratory

EM for LTP status

UVLA Testing: funct/perf.
testing completed
EMC testing on-going

Imperial College London

EM for LTP status

FEE EM: unit tested june03
Testing at UTN TP facility
is underway

ONERA

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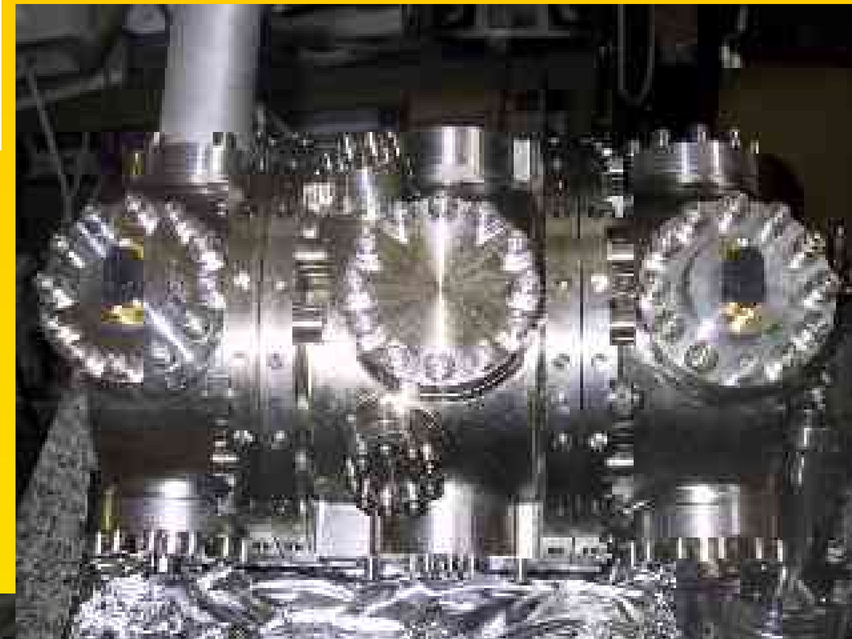
EM for LTP status

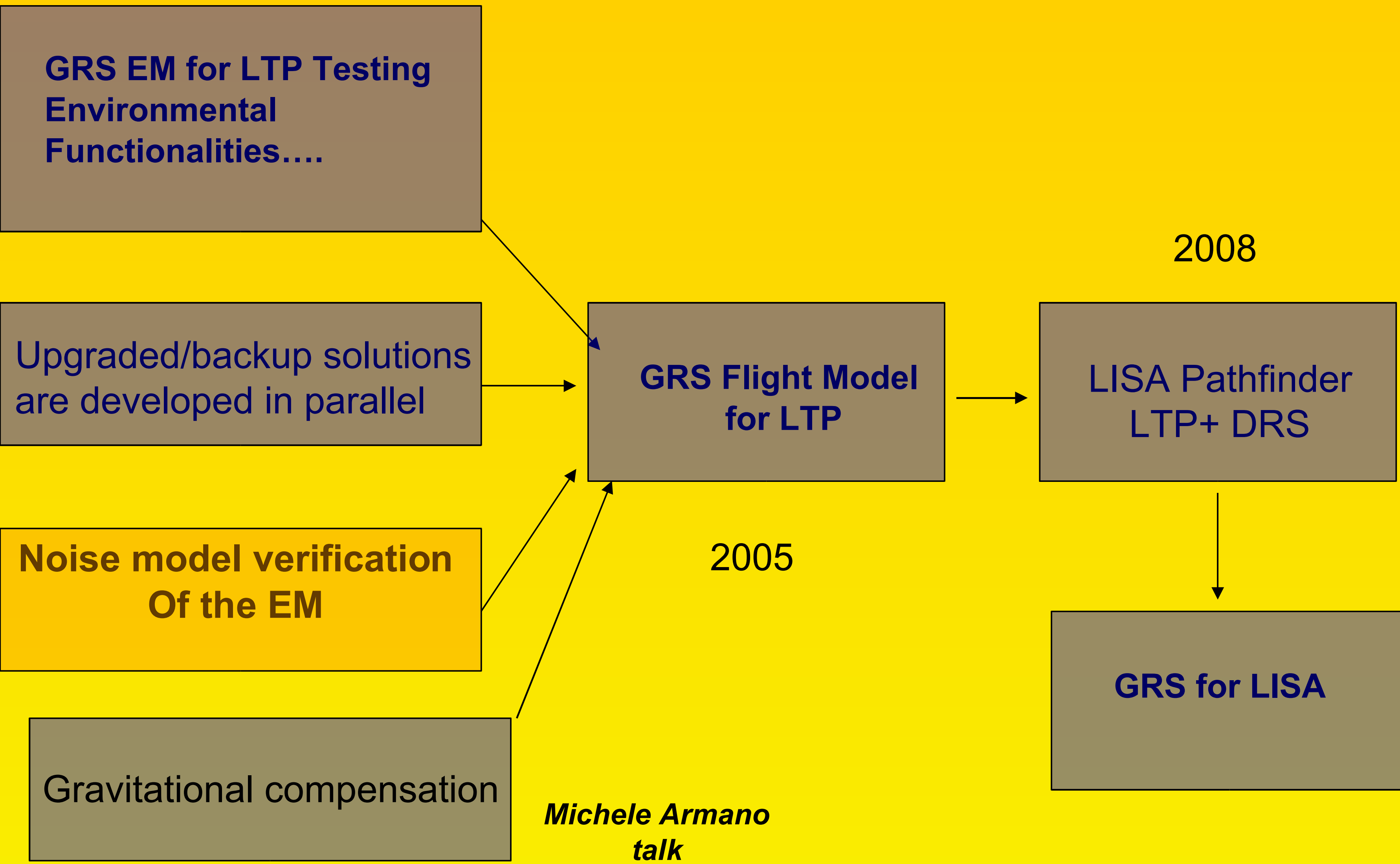
Testing Started at S/S level:

Intermediate vibration tests



Vacuum Enclosure:
integration and testing
on going

EM for LTP ⇒ FM for LTP ⇒ LISA

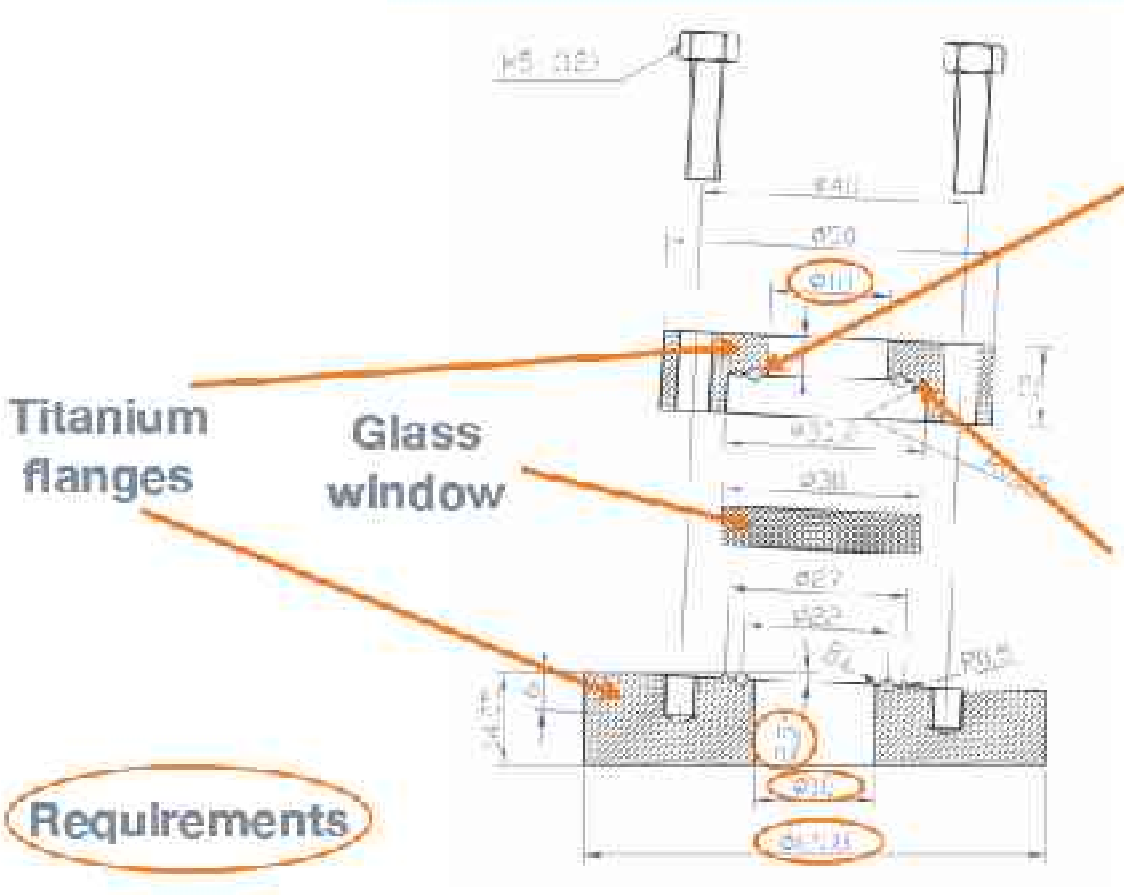


OPTICAL WINDOW alternative design: indium sealing/ glued

Gerhard Heinzel talk

- Window:
  - Ohara glass type S-PHM52 fine annealed
- Flange:
  - Titanium alloy (Ti 6Al4V)

By P. Bosetti, Matteo Benedetti, Vigilio Fontanari



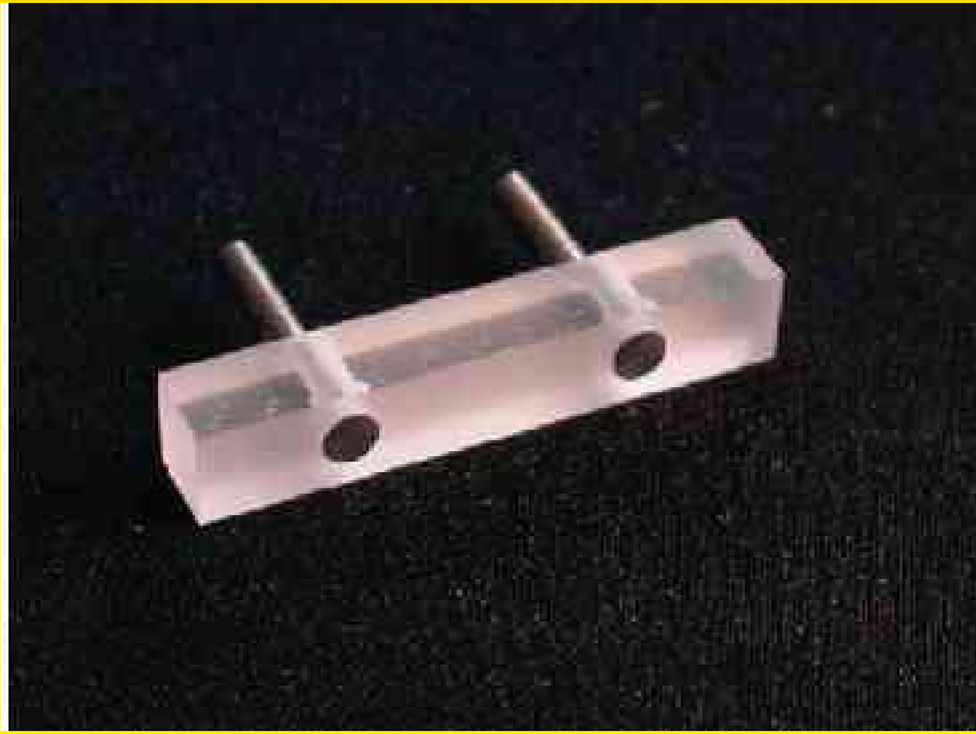
ELECTRODES ALTERNATIVE DESIGN

Sample #		Length [37.000 mm]	Height [6.000 mm]	Width [6.500 mm]
1	Avg.	37.946	5.993	6.500
	St. Dev.	0.000	0.000	0.001
2	Avg.	37.051	6.006	6.510
	St. Dev.	0.000	0.001	0.002
3	Avg.	37.948	5.948	6.520
	St. Dev.	0.001	0.001	0.000
4	Avg.	37.060	6.097	6.520
	St. Dev.	0.001	0.001	0.000

SAPPHIRE

no brazing

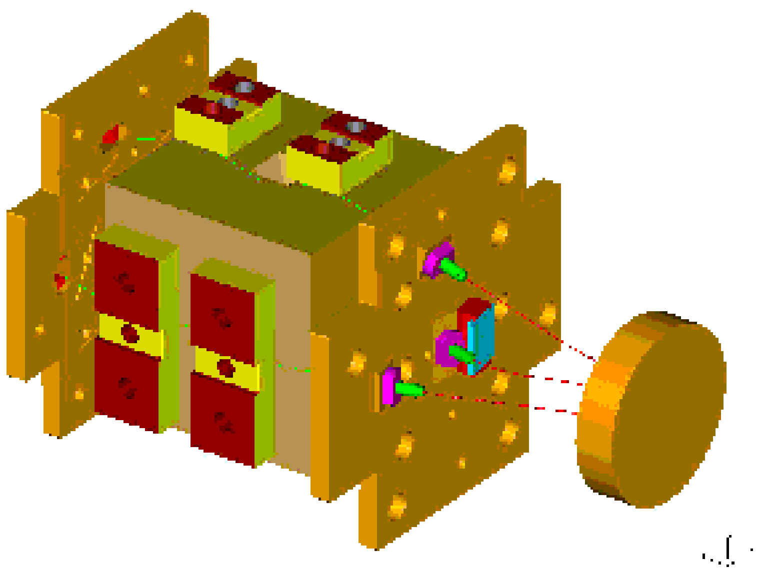
By I. Cristofolini and P. Bosetti

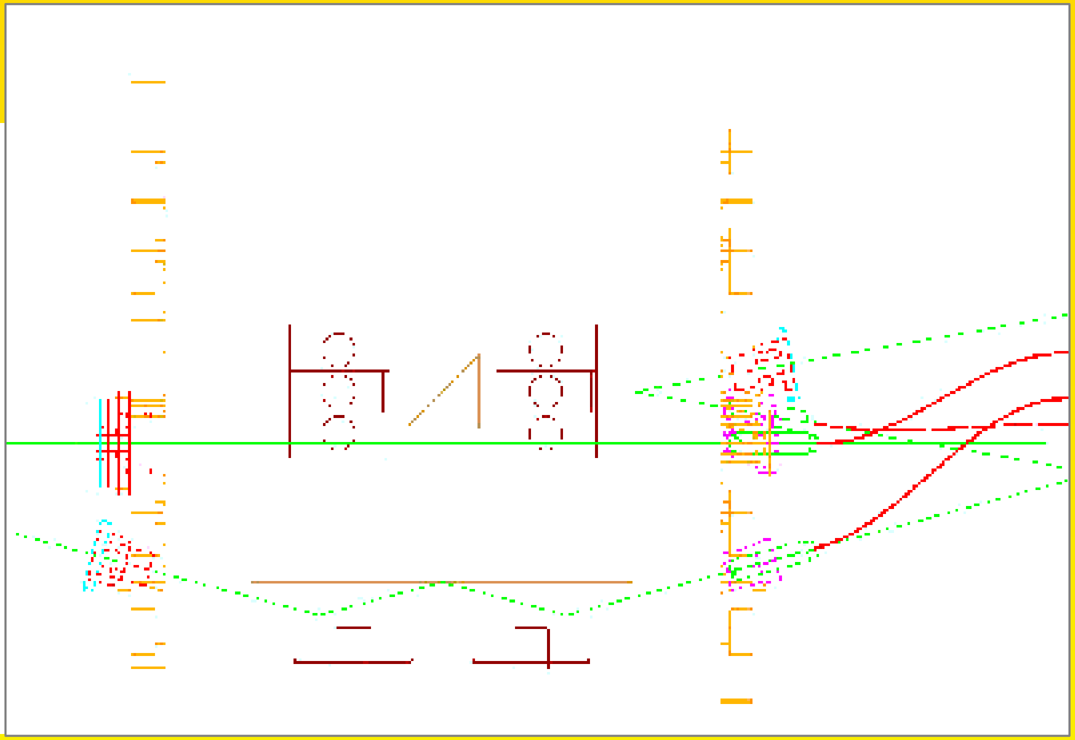


Implementation of the capacitive sensor with an optical read-out

Risk reduction
Higher sensitivities ,reduced cross talk

Talk of Luciano Di Fiore





NOISE MODEL

given a specific GRS configuration
identifies physical mechanisms and produces estimates for

displacement noise
force noise
stiffness

$$a_{residual} \approx \omega^2_{parasitic}\left(x_{noise} + \frac{F_{ext}}{M_{S/C}\,\omega^2_{fb}}\right) + \frac{f_{parasitic}}{m}$$

by means of model for the specific configuration and
assuming values for the parameters that enters in the model

Less known parameters???
Less knowledge -> more margin

Noise budget calculated both for LISA and LTP

NOISE BUDGET FROM NOISE MODEL OF GRS

LTP @ 1e-3 Hz		LISA @ 1e-4 Hz	
Noise source	**Value (m/s^2/vHz)**	**Noise source**	**Value (m/s^2/vHz)**
Thermal effects	5,1E-15	Thermal effects	4.20E-16
Brownian noise	1E-15	Brownian noise	1.20E-15
Cross-Talk, M3, TM1	2,7E-15	Cross-Talk	6.40E-16
Cross-Talk, M3, TM2	4,7E-15		
Magnetics S/C	1,5E-14	Magnetics S/C	6.00E-16
Magnetics, Interplanetary	4,3E-15	Magnetics, Interplanetary	6.90E-17
Random charging	2,6E-15	Random charging	9.40E-16
Various	4,3E-15	Various	1.00E-15
Actuation	5,2E-15		
Total	1,8E-14	Total	2.10E-15
Margin	2,1E-14	Margin	1.90E-15
Requirement	2,8E-14	Requirement	2.80E-15

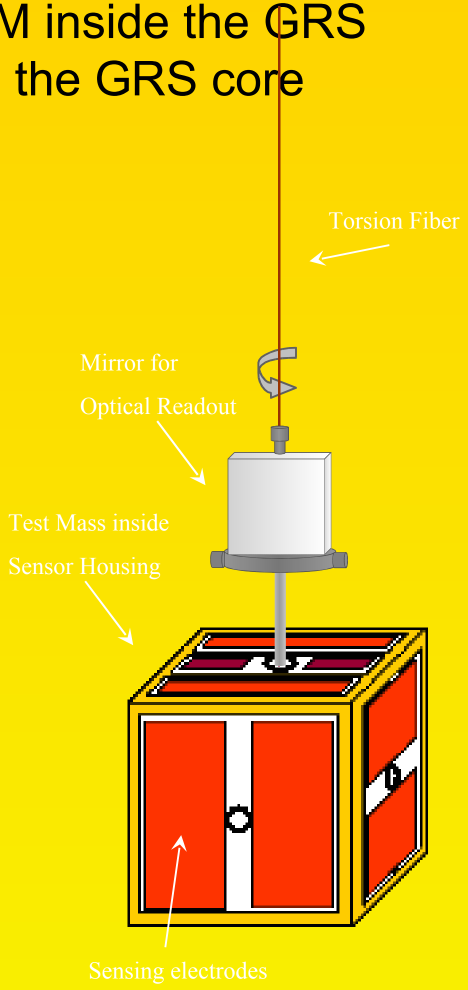
for LISA
Less hostile environment
Lower frequency
No actuation along sensitive axis

NOISE MODEL VERIFICATION

Verification of physical mechanism models and parameters measurement

Key instrument of this testing effort has been a torsion pendulum bench:

torsion pendulum with a hollow replica of the TM inside the GRS characterizes disturbances generated inside the GRS core



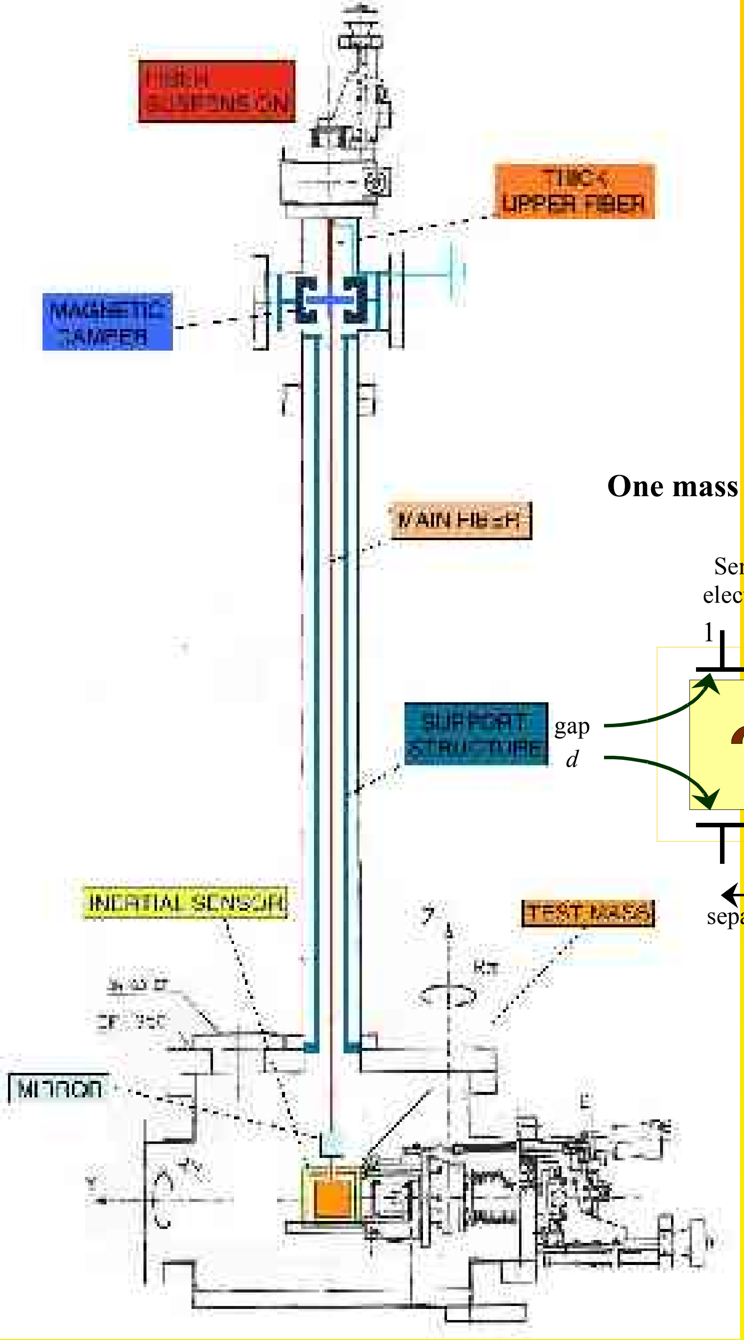
- **Place upper limit on force disturbances related with GRS and TM surface properties (no disturbances related to volume effect)**

- **Characterization of individual disturbance source**

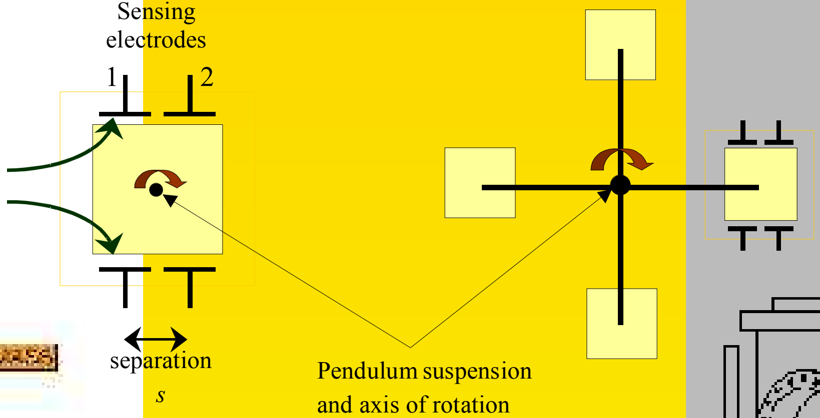
The source is modulated

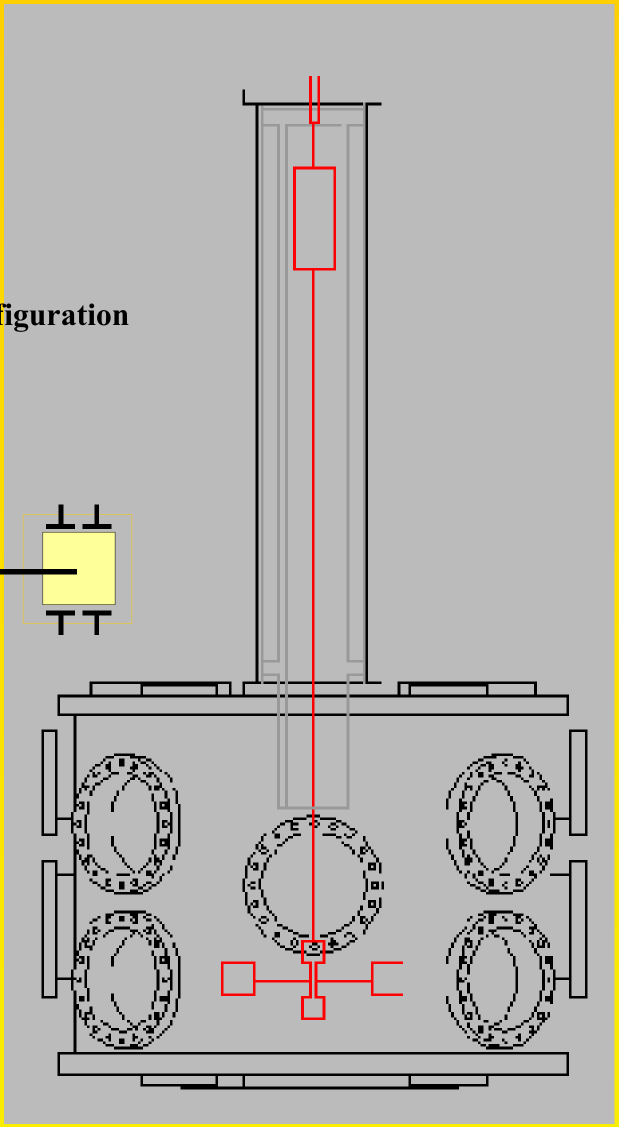
⇩

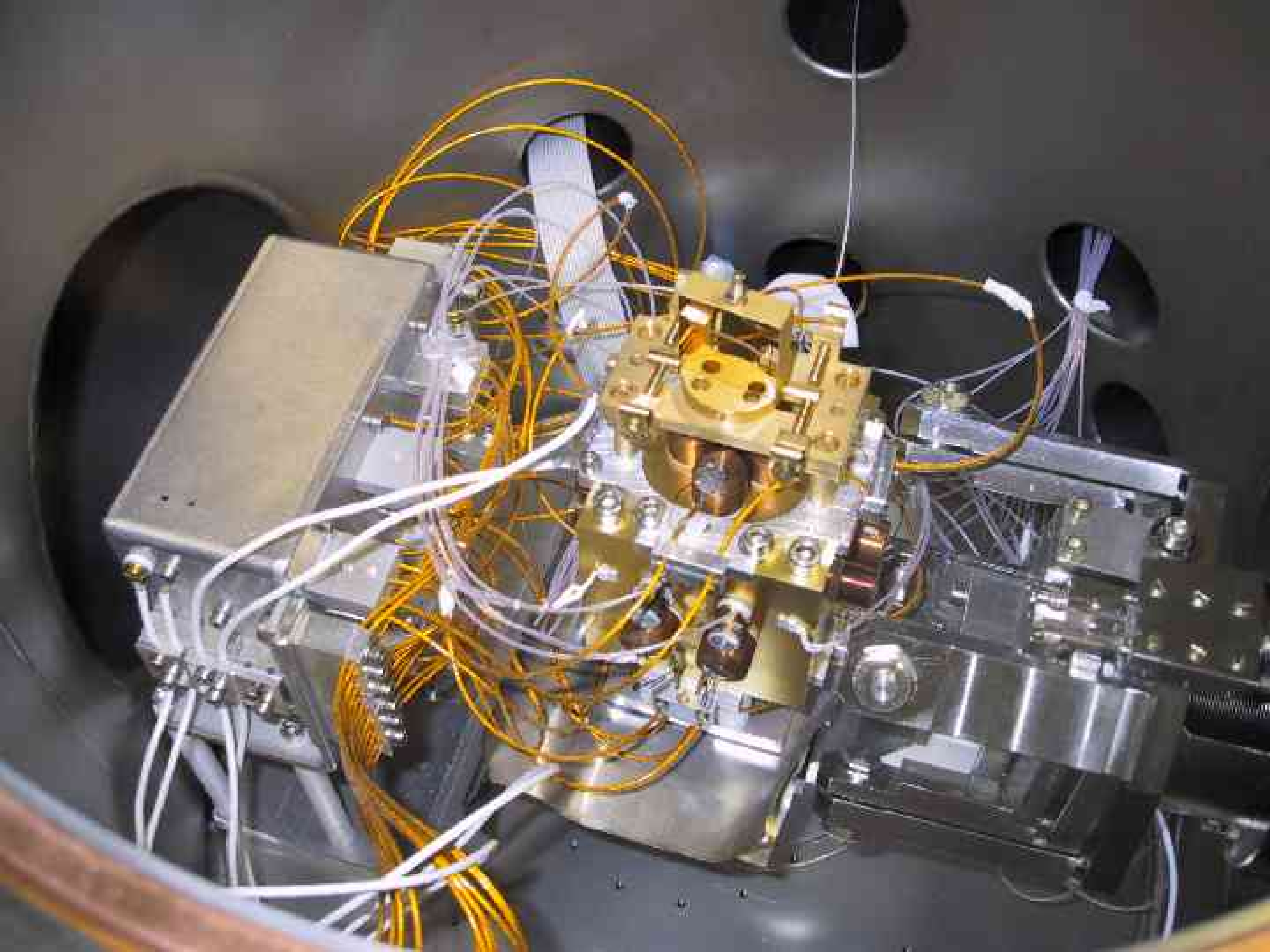
The torque exerted on the test mass is measured by coherent demodulation of the pendulum twist angle

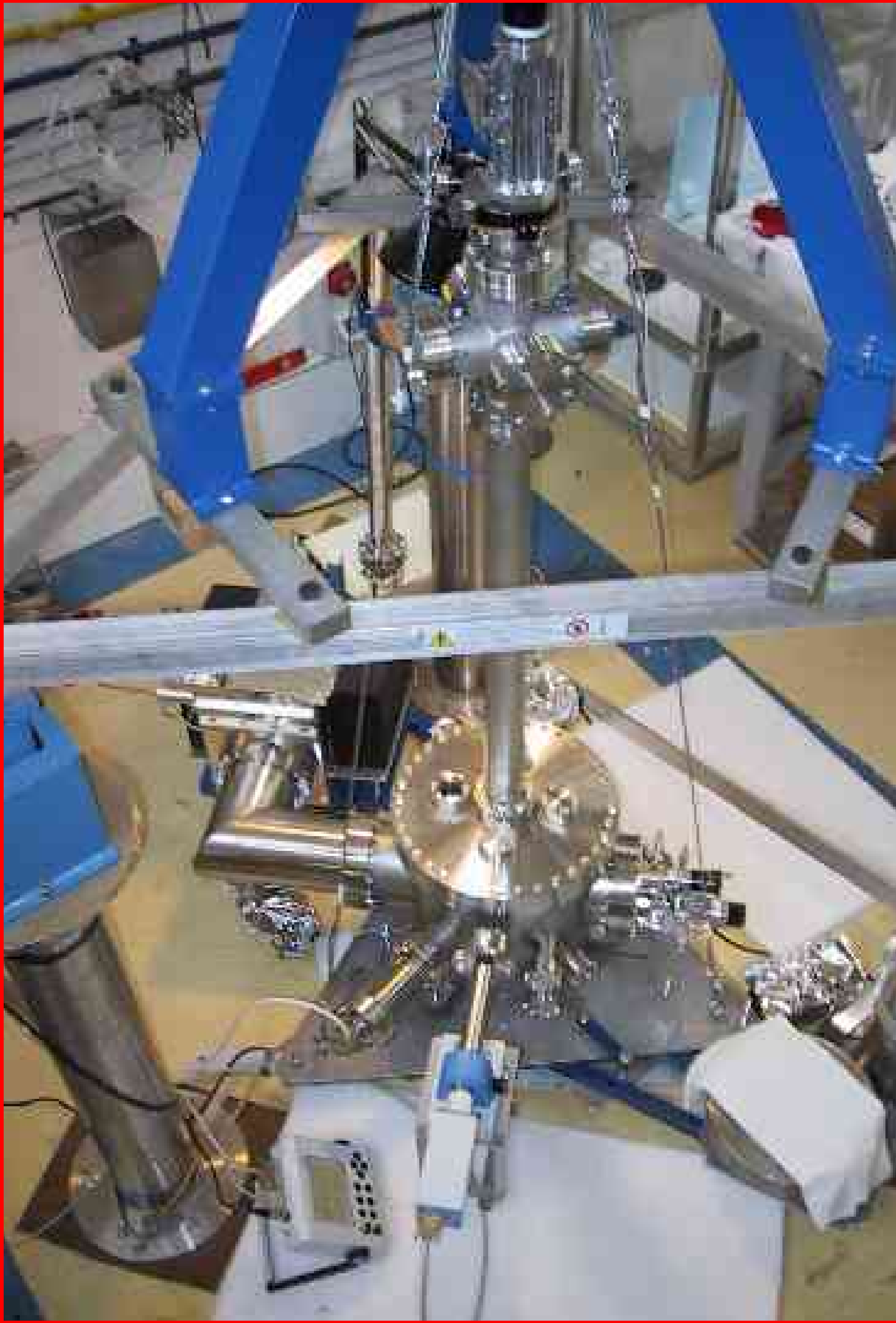


One mass configuration **Four mass configuration**










Achieving geodetic motion for LISA test masses: ground testing results

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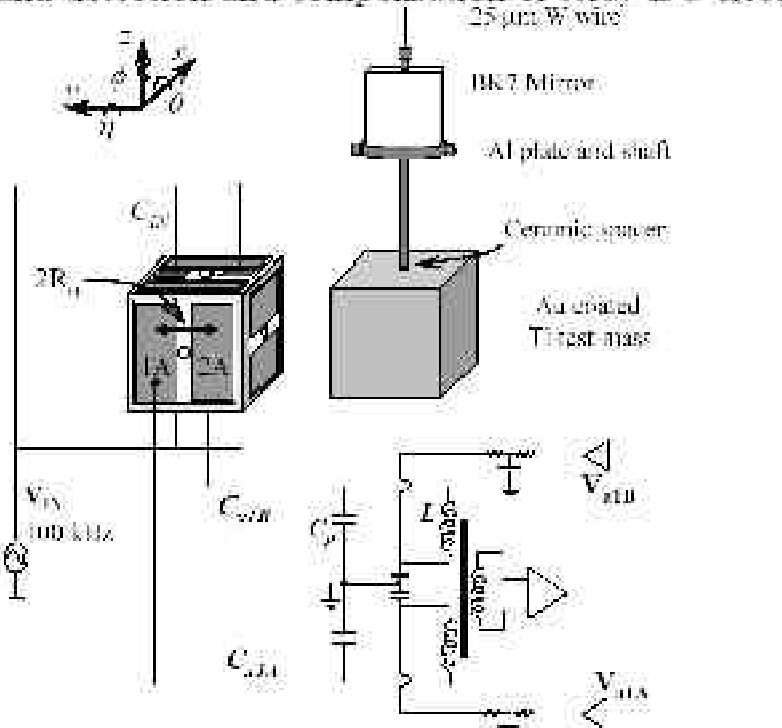
[2] *Centro Fisica degli Stati Aggregati, 38050 Povo (TN), Italy*

(Dated: August 14, 2003)

The low-frequency resolution of space-based gravitational wave observatories such as LISA (Laser Interferometry Space Antenna) hinges on the orbital purity of a free-falling reference test mass inside a satellite shield. We present here a torsion pendulum study of the forces that will disturb an orbiting test mass inside a LISA capacitive position sensor. The pendulum, with a measured torque noise floor below 10 fN m/√Hz from 0.6 to 10 mHz, has allowed placement of an upper limit on sensor force noise contributions, measurement of the sensor electrostatic stiffness at the 5% level, and detection and compensation of stray DC electrostatic biases at the mV level.



...G. 1: Sensor electrode configuration and circuitry, with

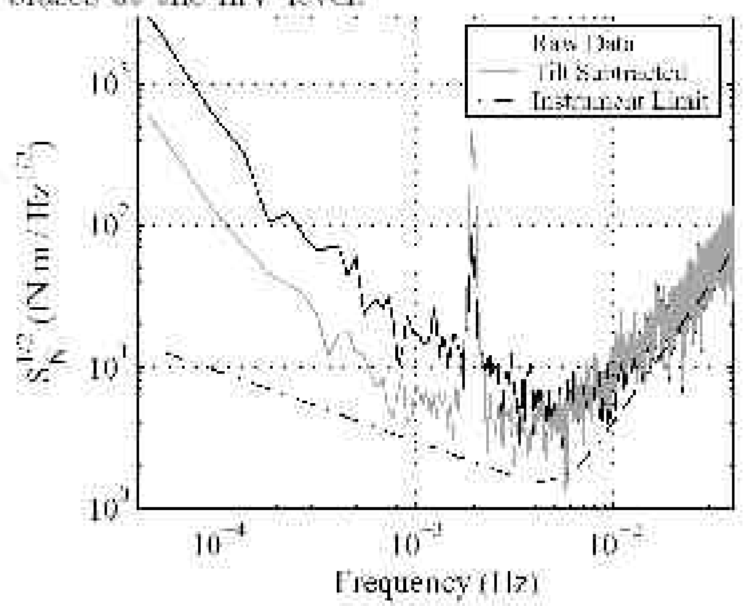
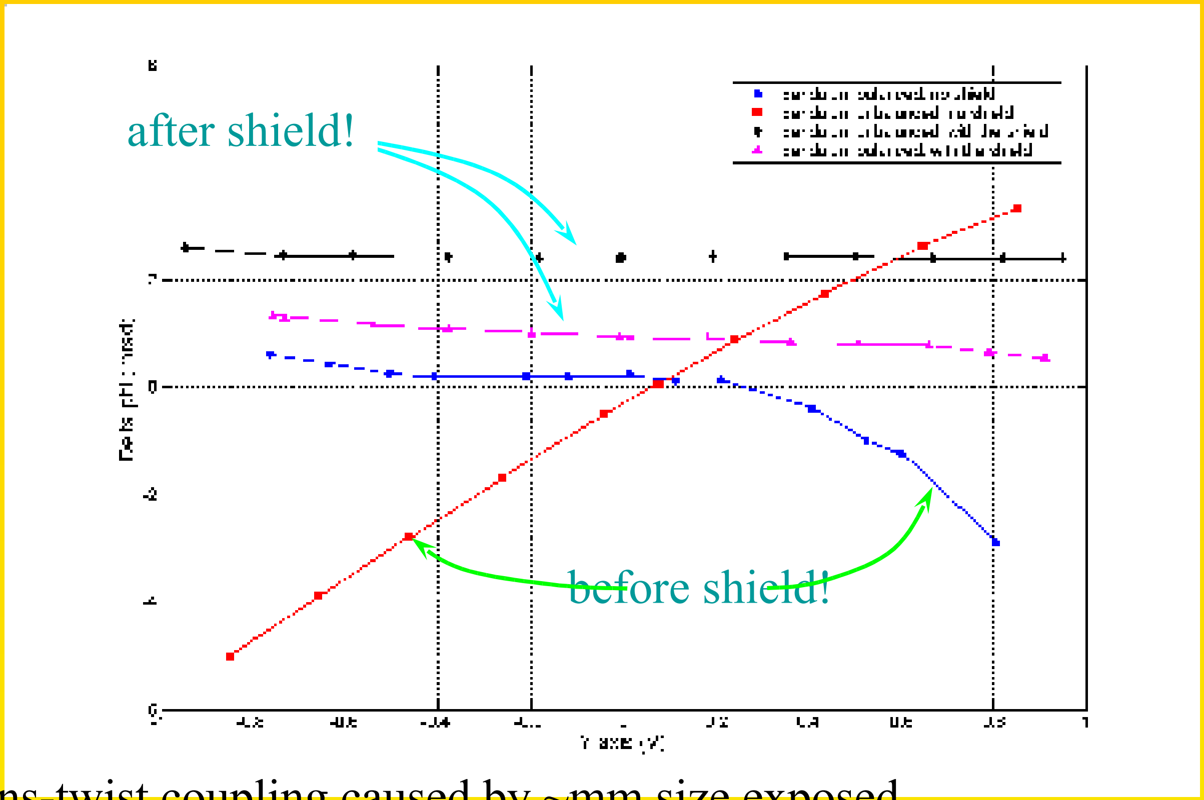


FIG. 2: Plot showing the raw (dark) and tilt subtracted (light) pendulum torque noise, with the instrument limit (dashed). Spectra for this 19 hour measurement are calculated with a 22,000 second Hanning window, which leaves an artificial peak near the 2 mHz pendulum resonance.

Phys. Rev. Lett. 2003

RENTO

Trans-twist coupling: understood and (nearly) eliminated

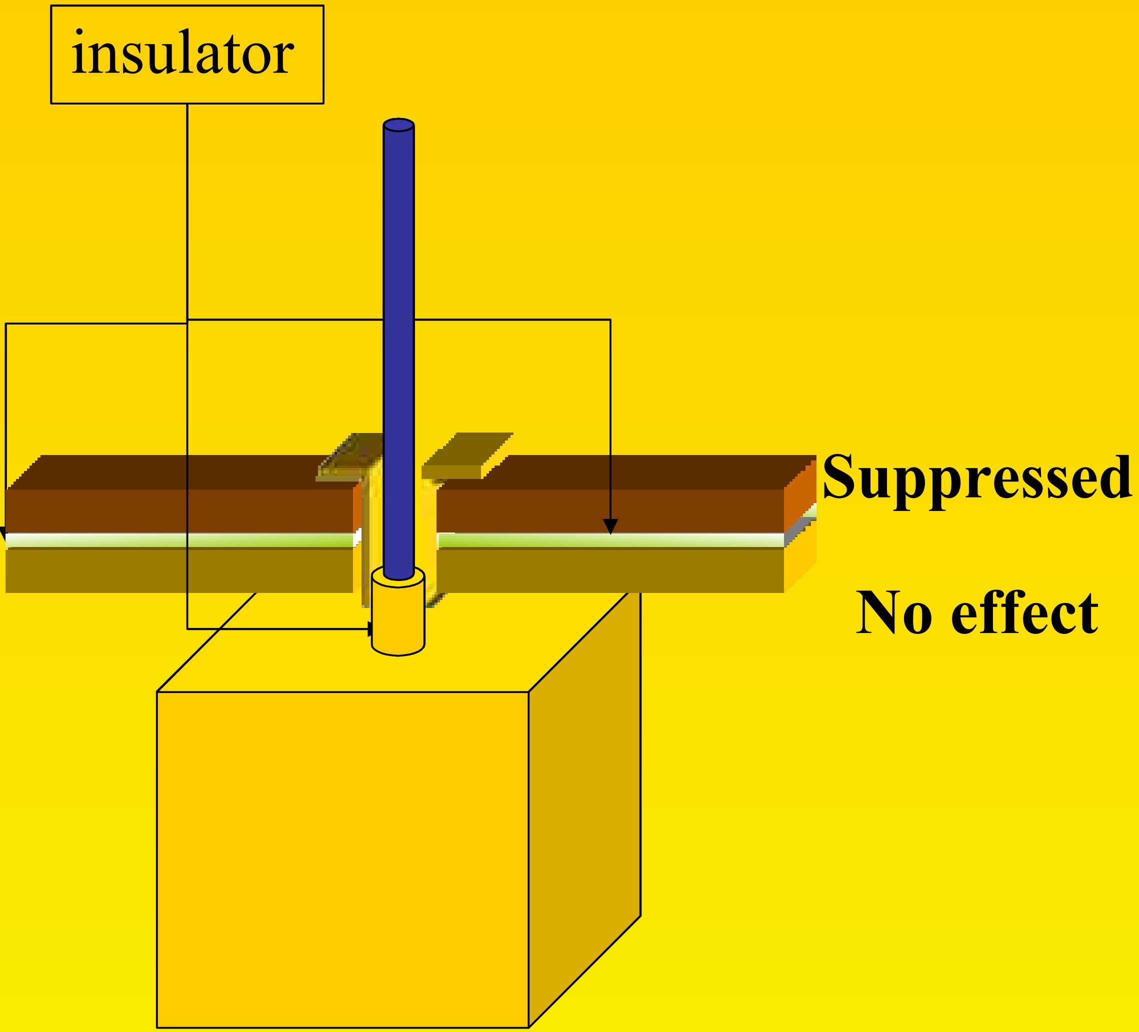


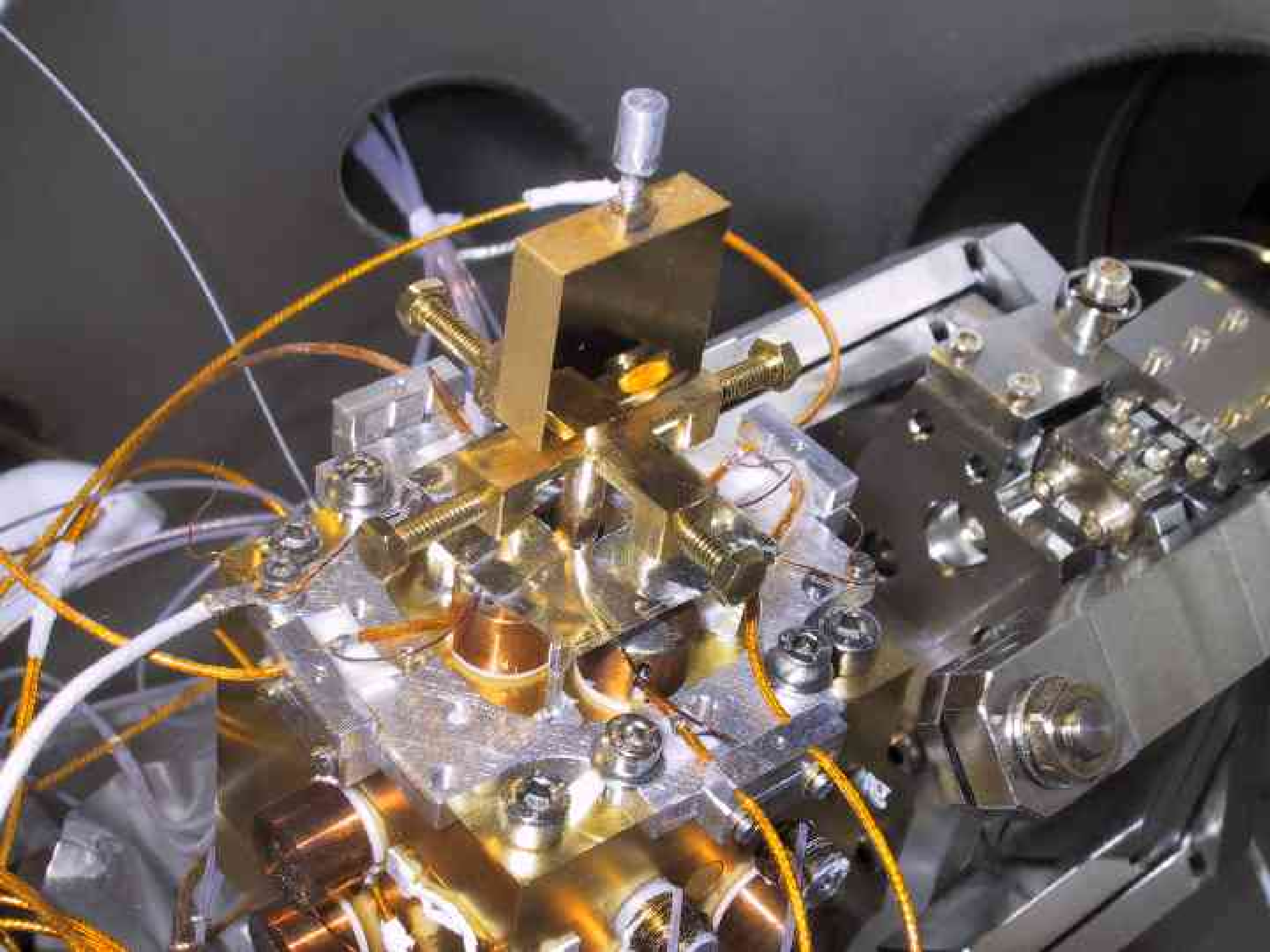
- inclination dependent trans-twist coupling caused by ~mm size exposed dielectric ~ .5 mm from pendulum axis
- effect removed by addition of thin electrostatic shield

Good news ... coupling originated in pendulum mount, not intrinsic to sensor

... shielding removed the coupling (and the resulting noise)

Bad news ... any bare dielectric in vicinity of sensor is a disaster! (F ~ 100 nN)


insulator
Suppressed
No effect



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CURRENT 1 MASS PENDULUM PERFORMANCES

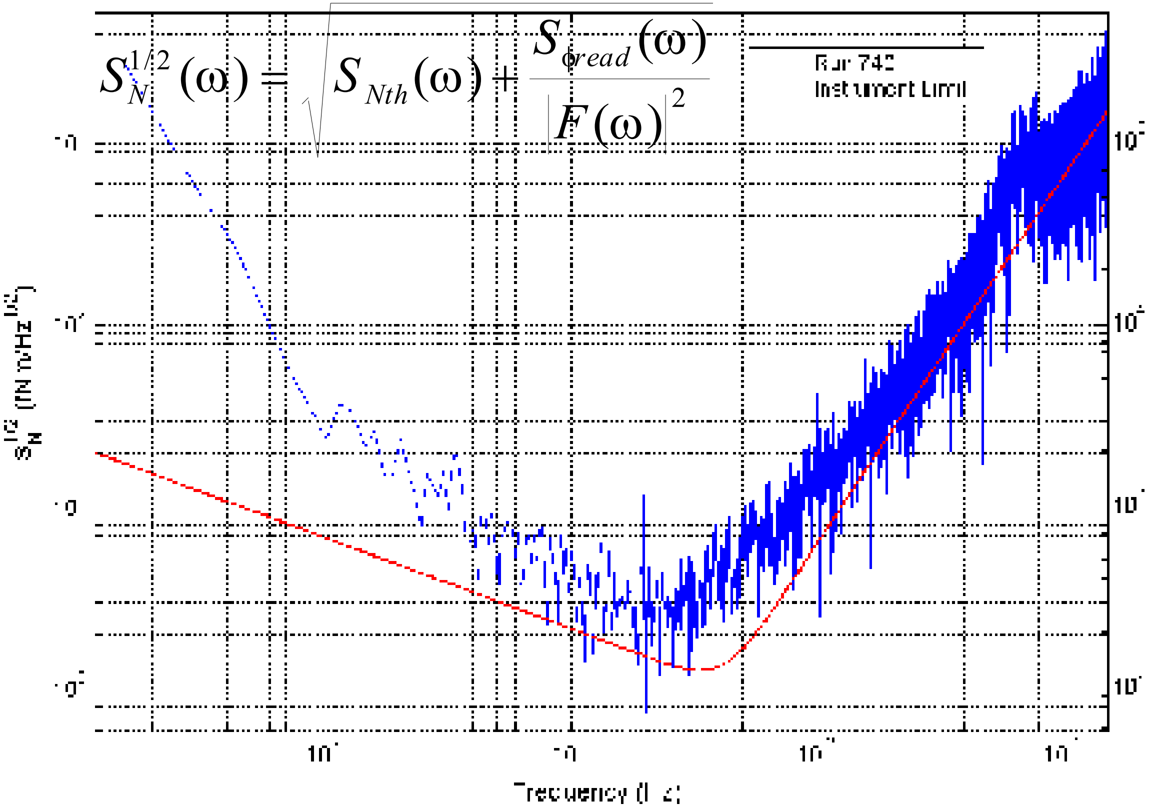
Upper limit on sensor force noise contributions

4E-4 5E-3 Hz torque noise below 10 fN m/sqrt(Hz)

acceleration noise for a bulk LISA test Mass of the same size 1e-12 m/s^2/sqrt(Hz)

@ 3e-3 mHz -> 4e-13 m/s^2/sqrt(Hz) (factor 10 over the LTP flight test goal)

$$S_N^{1/2}(\omega) = \sqrt{S_{Nth}(\omega) + \frac{S_{\phi read}(\omega)}{|F(\omega)|^2}}$$

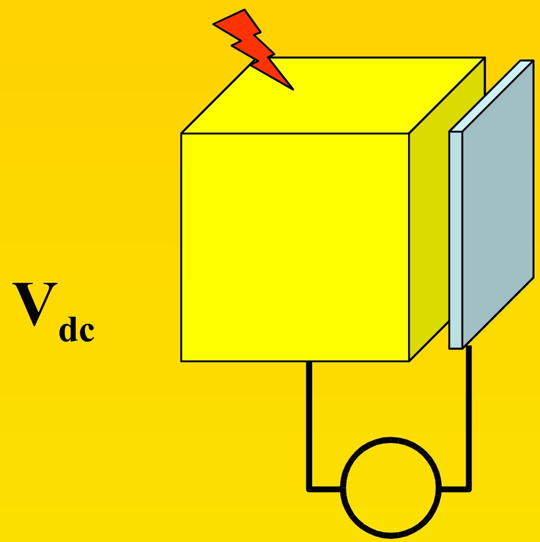


Coherent torque measurement

Frequency of applied disturbance (mHz)	Resolution (Nm) (3 hours integration time)
0.1	4×10^{-16}
1	5×10^{-17}
5	8×10^{-17}
10	2×10^{-16}

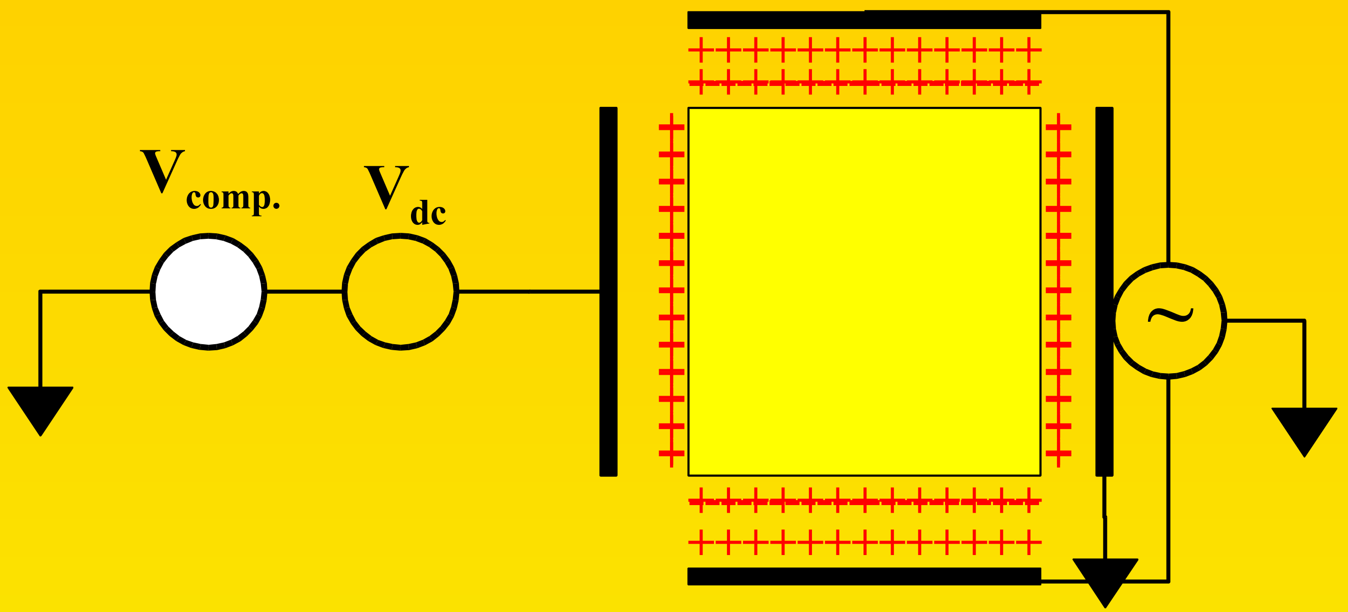
Verify the model by measuring the "transfer fuction" of that effect and measure the parameters!!

Stray dc voltage + Random arrival of charge



Random force acting on the test mass

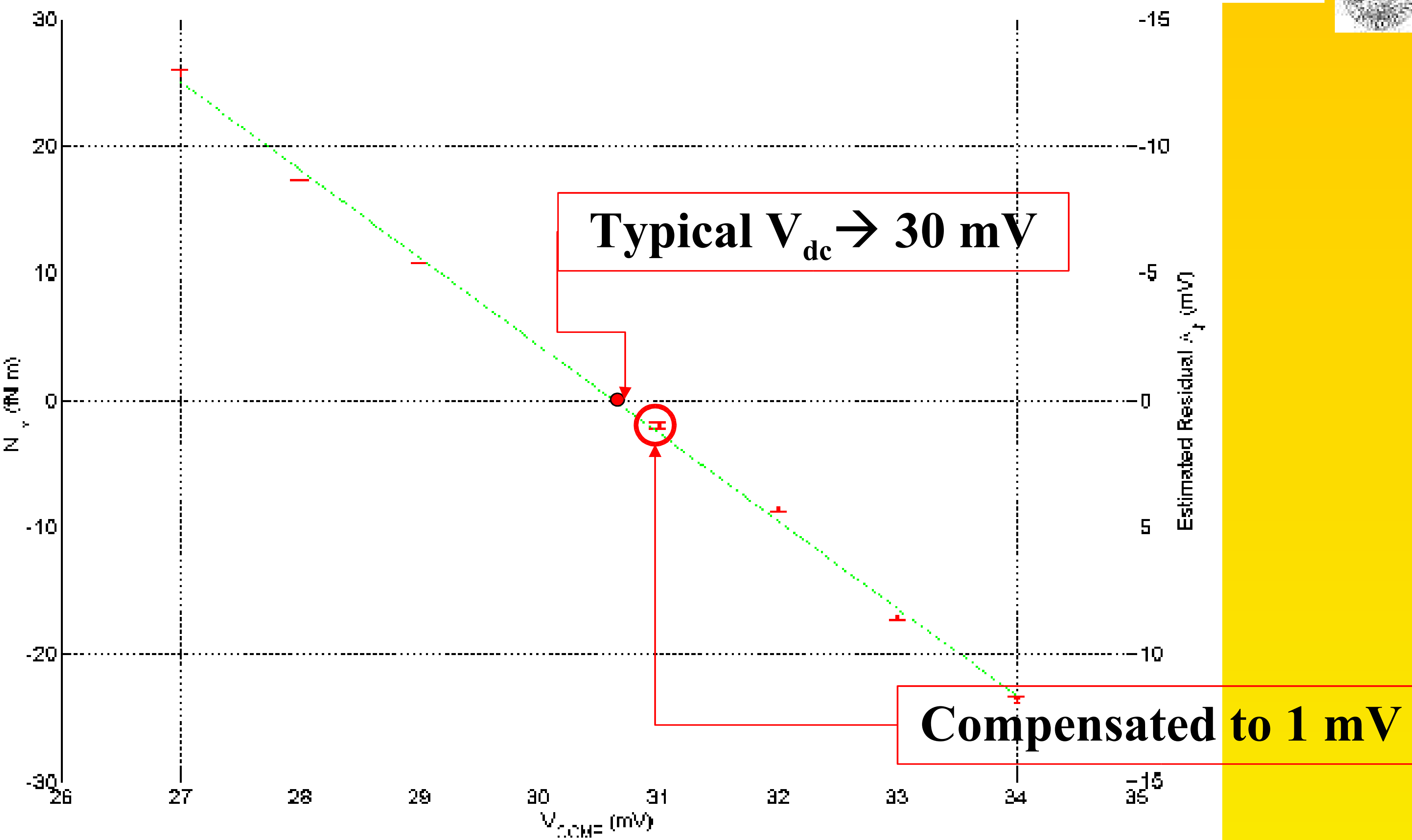
$$\frac{S^{1/2}(\omega)}{m_o} = 0.8\times 10^{-15}\ \frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}\left(\frac{4\ \mathrm{mm}}{\mathrm{gap}}\right)\left(\frac{V_{dc}}{10\ \mathrm{mV}}\right)\left(\frac{\mathrm{event\,rate}}{300\ \mathrm{s}^{-1}}\right)^{1/2}\left(\frac{0.1\mathrm{mHz}}{f}\right)$$



Simulating a varying charge on the test-mass → ac-torque induced

V_{dc} may be compensated → $V_{dc}+V_{comp.}=0$

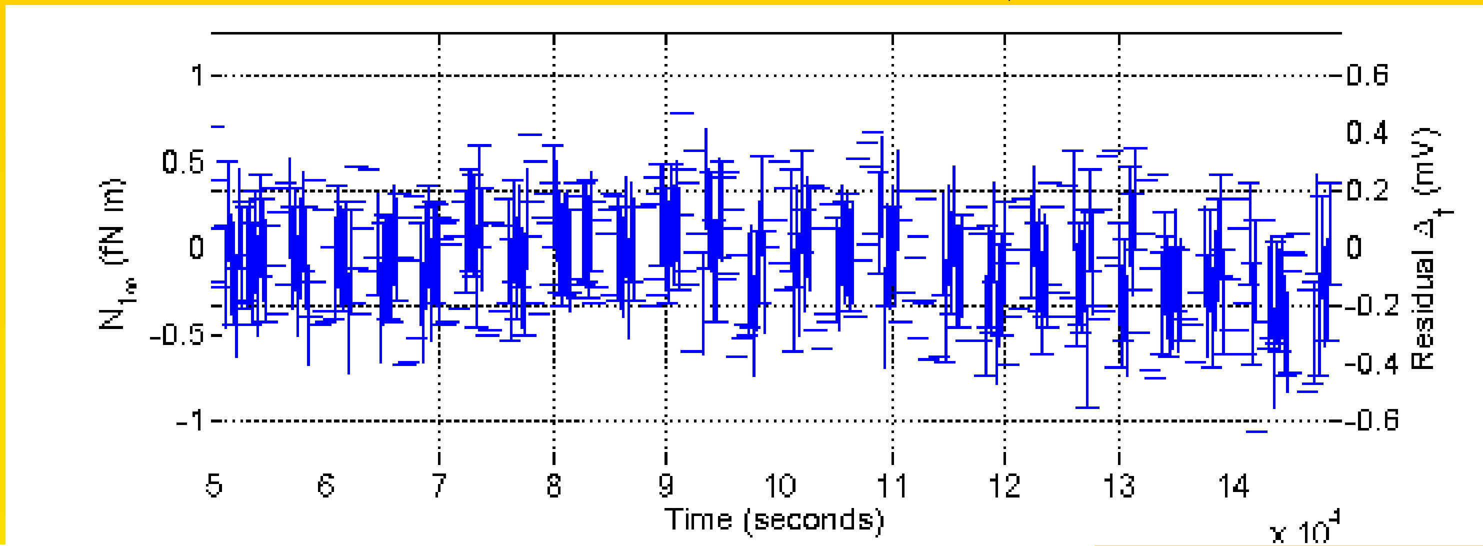
Torque on test-mass (fN m)

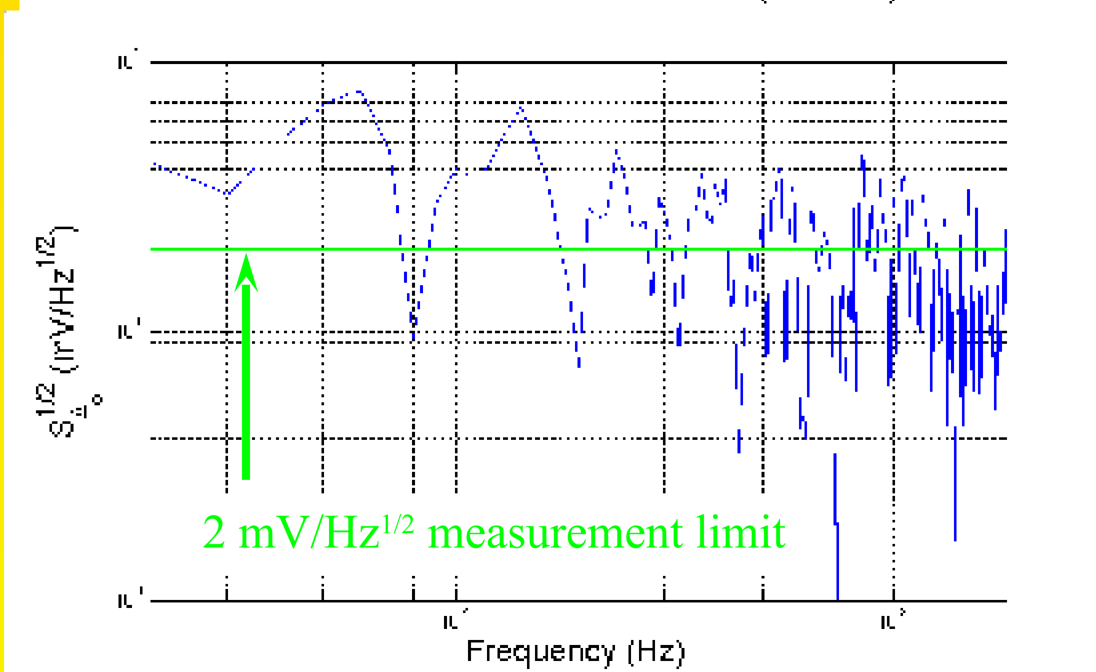


Compensation voltage on electrodes (mV)

DC Bias measurements: stability

28 Hour measurement of residual Δ_ϕ with V_{COMP} = 20 mV

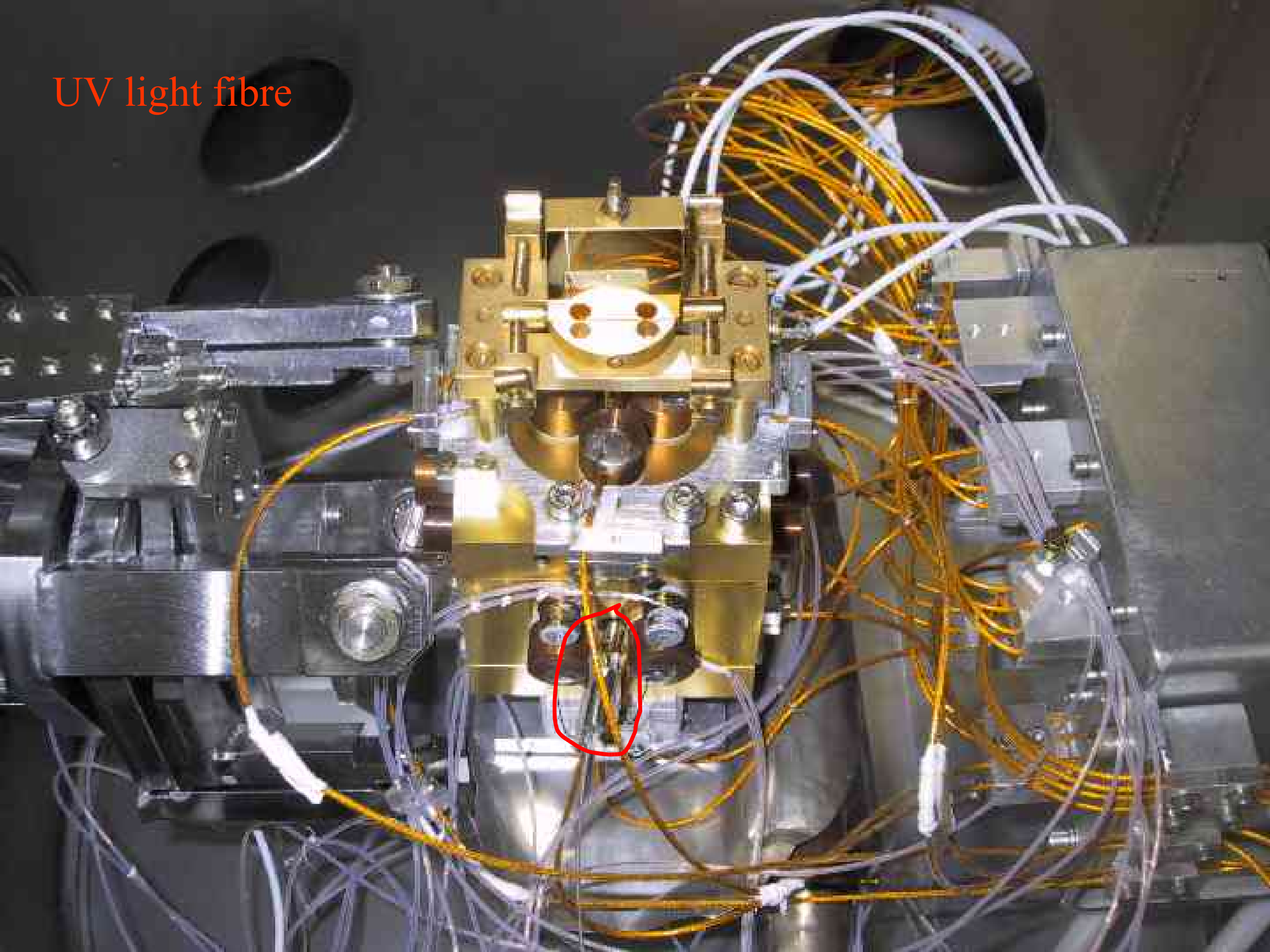




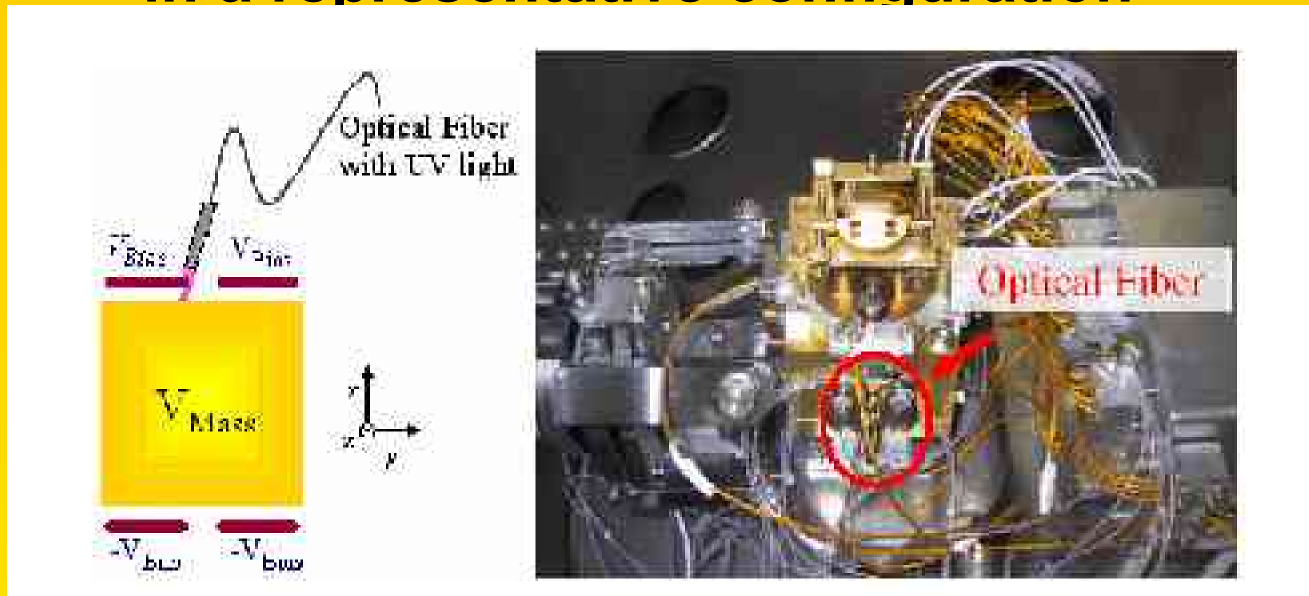
DC bias stability

$S^{1/2}_{\Delta\phi}$ < 2 mV /Hz for f ~ mHz

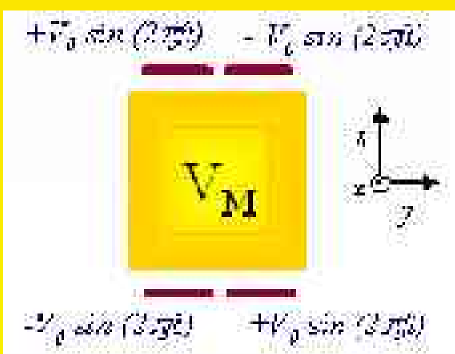
preliminary


UV light fibre

Charge management: demonstration of charge transport in a representative configuration



- currently using a single UV fiber to illuminate both TM and an *x*-sensing electrode
- apply DC voltage V_{BIAS} to electrodes to bias charge transport (bipolar)



Charge measurement technique
3000 e

Relevant LISA discharge threshold
10^7 charges

Coherent measurement technique results

With a 2 mm gap breadboard prototype (will be repeated with the EM for LTP)

(Talk of Ludovico Carbone)

Noise source type	Less known effect/parameter	Assumed in the noise model	Measured (torsion pendulum in Trento)
Thermal effects	Temperature dependent outgassing Outgassing rate and its activation energy	@ 293 K 1.4 x radiation pressure fluctuation effect	@ 295 K <0.3 x radiation pressure fluctuation effect (preliminary)
Random charging	Stray dc bias	100 mV (LTP) 10 mV (LISA)	Compensated @ mV level
Brownian noise	Sensing capacitive loss angle Dielectric losses	δ=1e-5	δ=1e-6

Moreover

Measurement of full sensor-test mass coupling at 5 % level

Sensing electrostatic stiffness in agreement with finite element calculation

1 mass torsion pendulum is limited:
Sensitive to torque rather than translational force
Performances close to the thermal noise
It has only a single DOF

On going facilities upgrading

Improve representativeness:
Testing directly the translational degree of freedom
Facilities with more than one force sensitive degree of freedom

Improve sensitivities: high Q fiber!

Bulk magnetic properties measurements

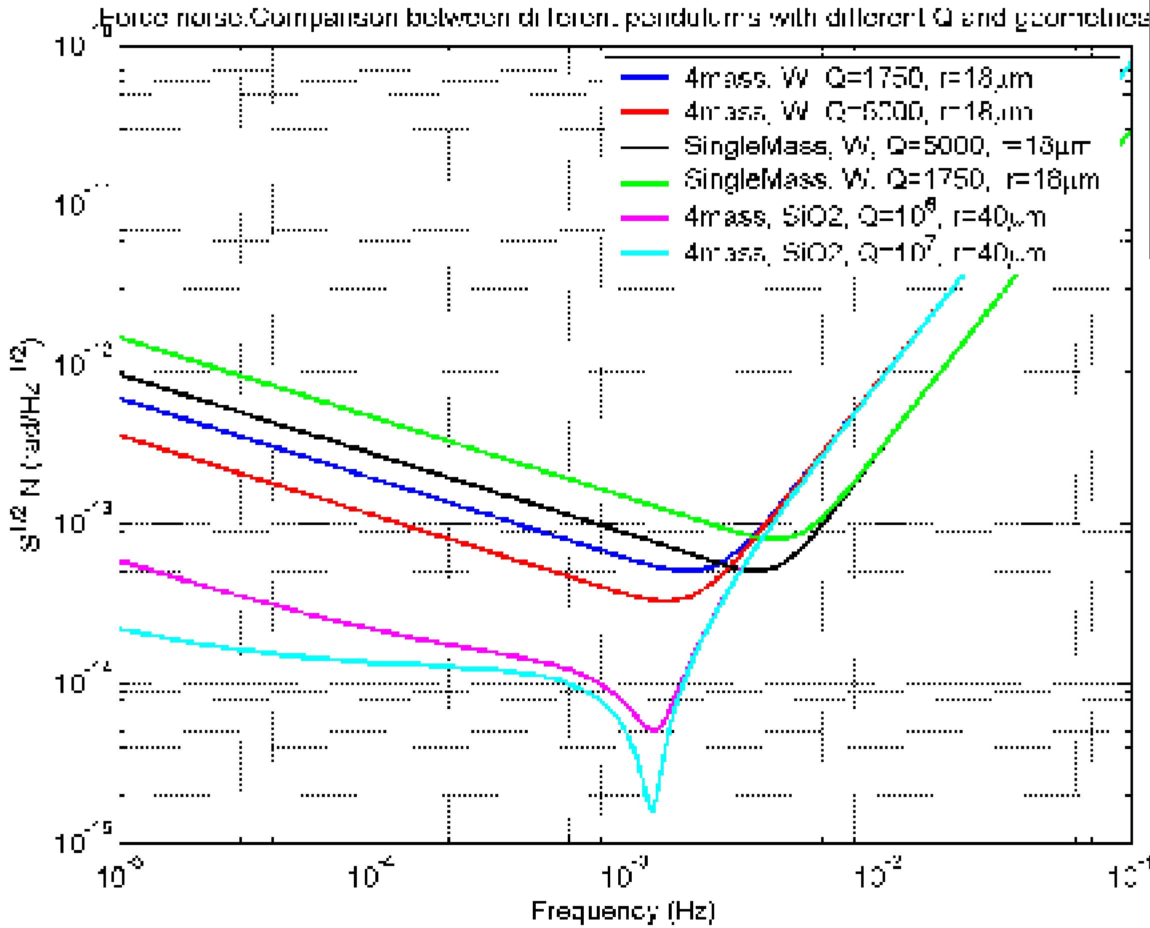
Additional functionalities:
implement the identified actuation scheme
and test the low frequency suspension

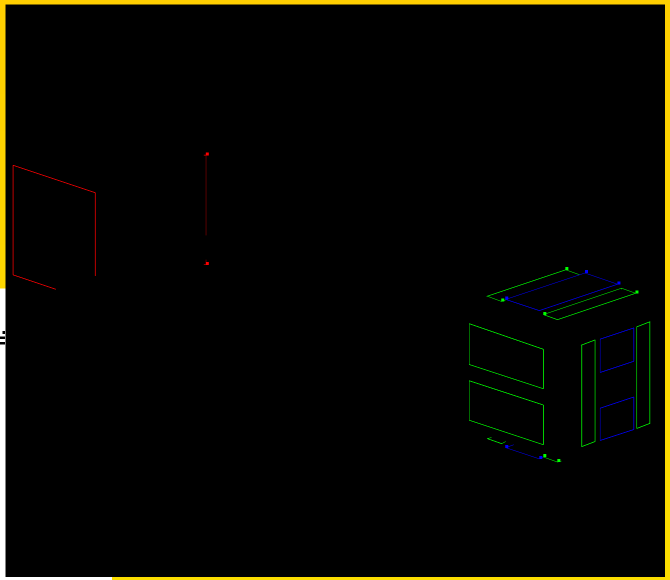
Test of in flight TM release

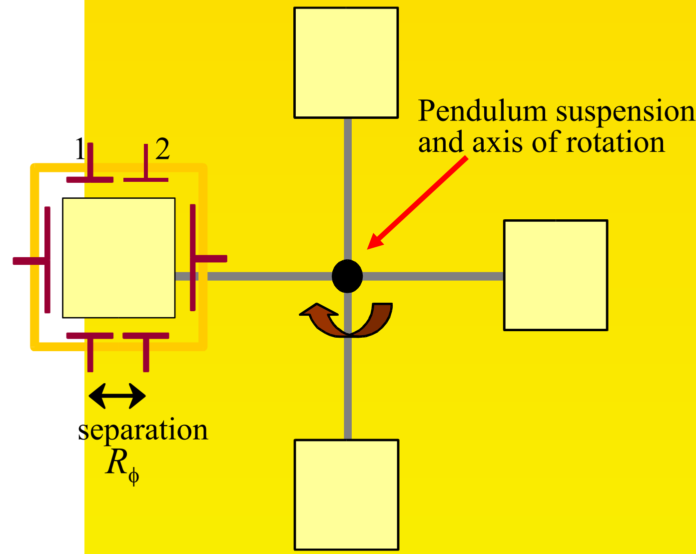
4 mass pendulum: testing directly the translational degree of freedom

- Translational force measurements
- total translational stiffness search
- cross-coupling into

- Upgrading: higher Q







Facilities with more than one “soft” force sensitive degree of freedom

Allows for:

Measuring forces and stiffness simultaneously along different degrees of freedom

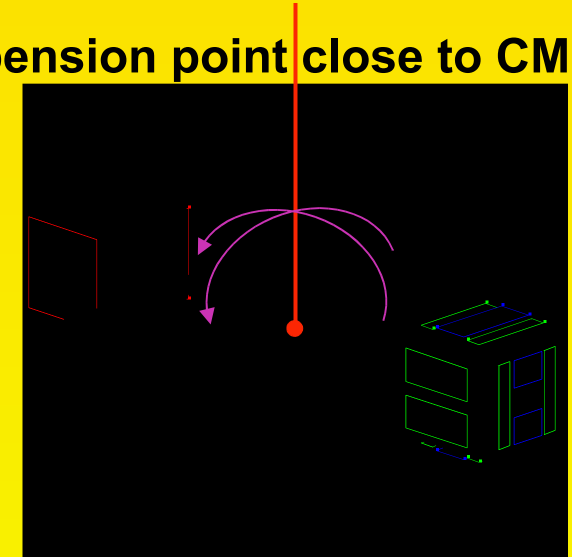
More effective in identifying and debugging spurious effects

Allows for testing of actuation cross talk with closed feedback loops:
in particular, it allows to measure the residual disturbance
along the sensitive translational axis when we close the control loop along the φ rotation
(because is the control loop that will be used also in LISA)

Allows for measuring the stiffness and cross-stiffness simultaneously along different DOF

Verification of the compatibility of the charge measurement by means of a dithering voltage
applied in terms of noise induced in x.

suspension point close to CM: 3 soft DOF

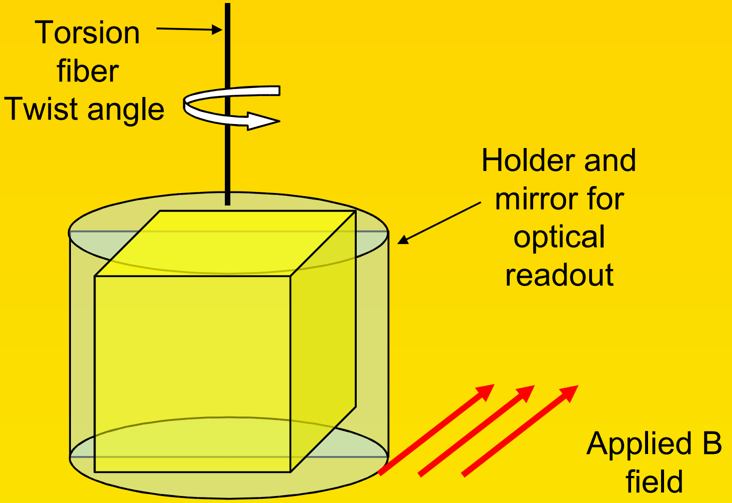


Tradeoff is ongoing to identify other Configurations

LISA PF INFN collaboration at LNGS

Magnetic Testing

- Measuring LISA TM magnetic properties (residual moment and susceptibility)
- Torsion pendulum technique



Measurement of *magnetic moment:* $\vec{m}(t) = \vec{m}_0 + \frac{\chi V}{\mu_0} \vec{B}(t)$

$$\left|\vec{N}(t)\right| = \left|\vec{m}(t) \wedge \vec{B}(t)\right|$$

$\left|\vec{m}_0\right| \leq 10^{-8}\,\mathrm{A} \cdot \mathrm{m}^2$

- Residual moment detection with homogeneous field
- Measurement of susceptility (χ) requires non-zero second derivative of B (in progress)

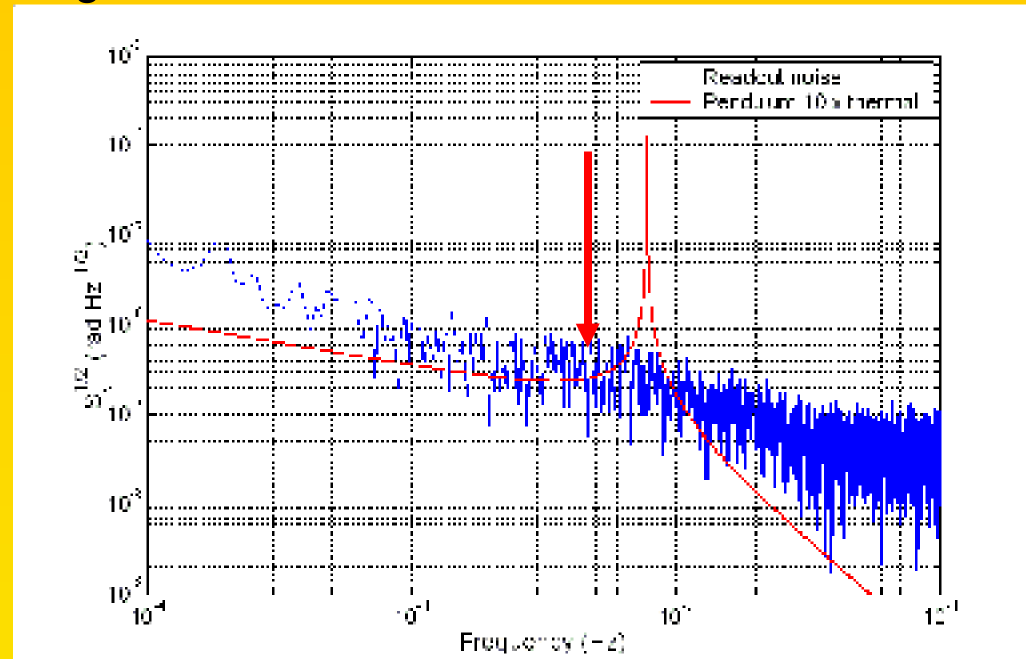
$|\chi| \leq 10^{-5}$

LISA Test Mass magnetic moment : full sized TM

Considering full sized TM:

- L = 46mm, weigh ≈2kg
- ≈230 g Al sample holder
- 110 μm W fiber, loaded to ≈65%
- ($\Gamma_f \approx 2 \cdot 10^{-6}$ Nm/rad)
- Quality factor Q=1000
- Readout limited noise:

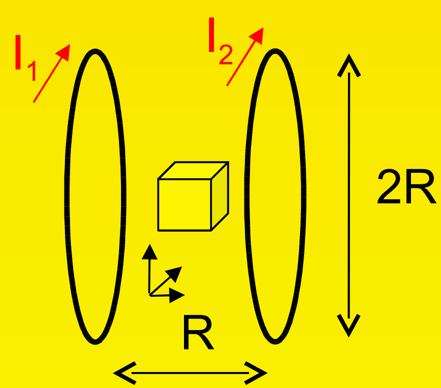
At 3 mHz: $\sqrt{S_\phi} \approx 10^{-6} \frac{\text{rad}}{\sqrt{\text{Hz}}}$



Assuming integration time: $T \approx 10^4\,\text{s}$ and field $|\vec{B}| \approx 10^{-4}\,\text{T}$

$$|\delta \vec{m}_0| = \sqrt{\frac{S_\phi}{T}} \frac{\Gamma_f}{|\vec{B}|} \approx 2 \cdot 10^{-10}\,\text{A} \cdot \text{m}^2$$

running Helmholtz coils to obtain uniform field



Coil features:

- R = 45 cm
- I ≈ 1 A, current in phase on both coils

Importance of on ground testing techniques development

•Verification of GRS performances

• Unique test procedures relevant to precision measurement science

• Techniques will be implemented in flight with LTP

•In principle,
the “subtraction tecnique” would allow with the LTP
to detect residual acceleration below the expected limit

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