Results from Torsion Pendulum Ground Testing of LISA Gravitational Reference Sensors

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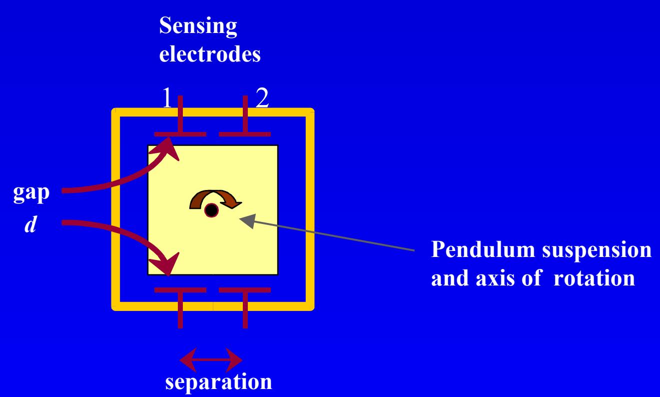
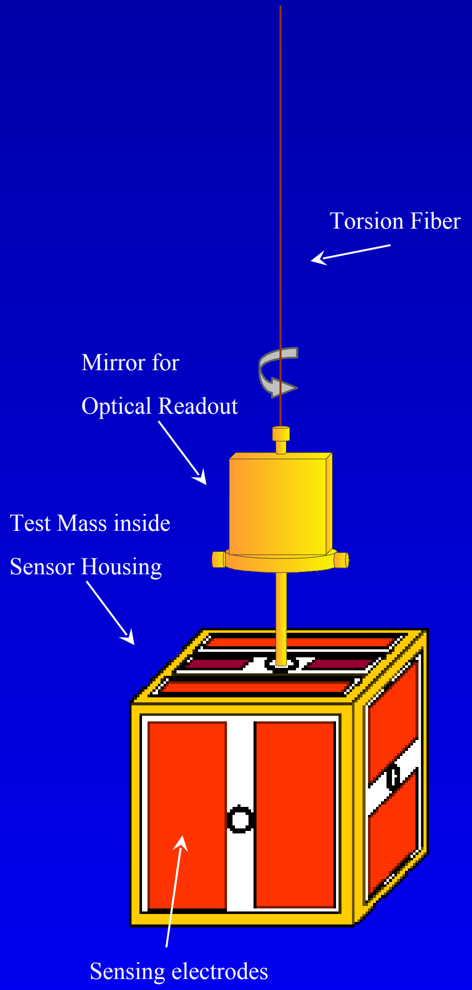
Torsion Pendulum Ground Testing of GRS

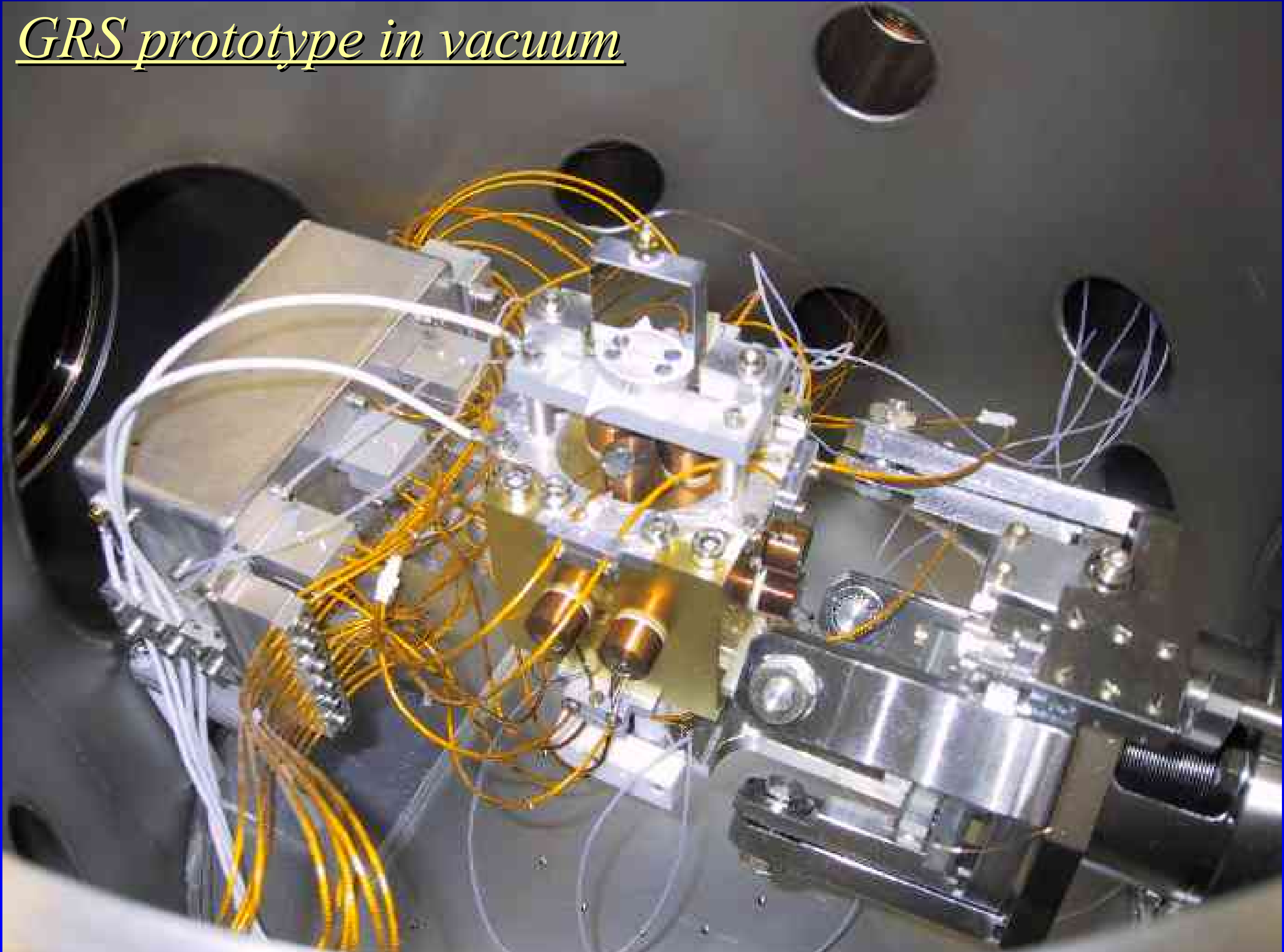
- Light-weight test mass suspended as inertial member of a low frequency torsion pendulum, surrounded by sensor housing
- Measure stray forces as deflections of pendulum angular rotation
- Precise study of residual couplings to sensor and disturbance sources



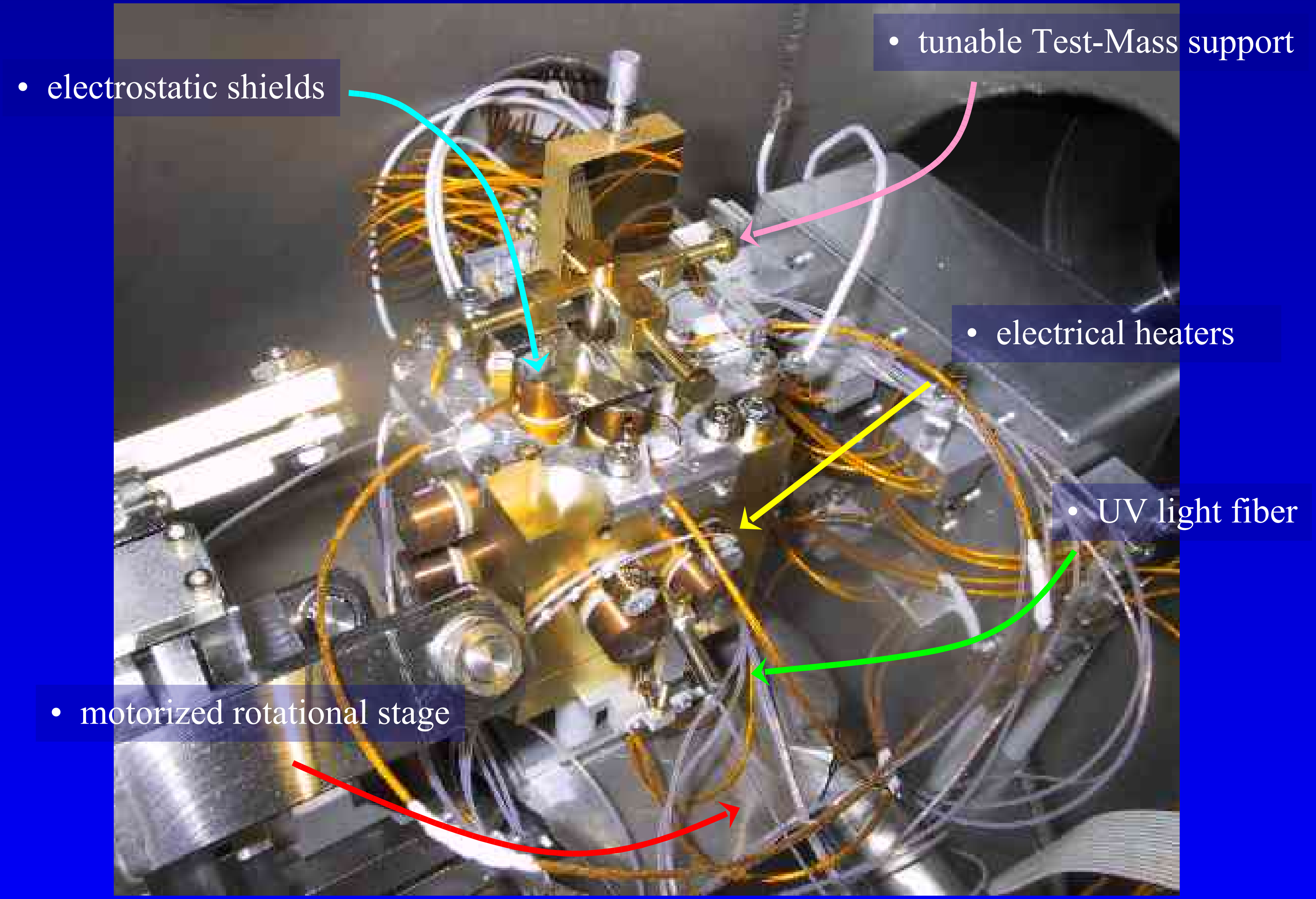


The Trento Torsion Pendulum Facility

GRS prototype in vacuum

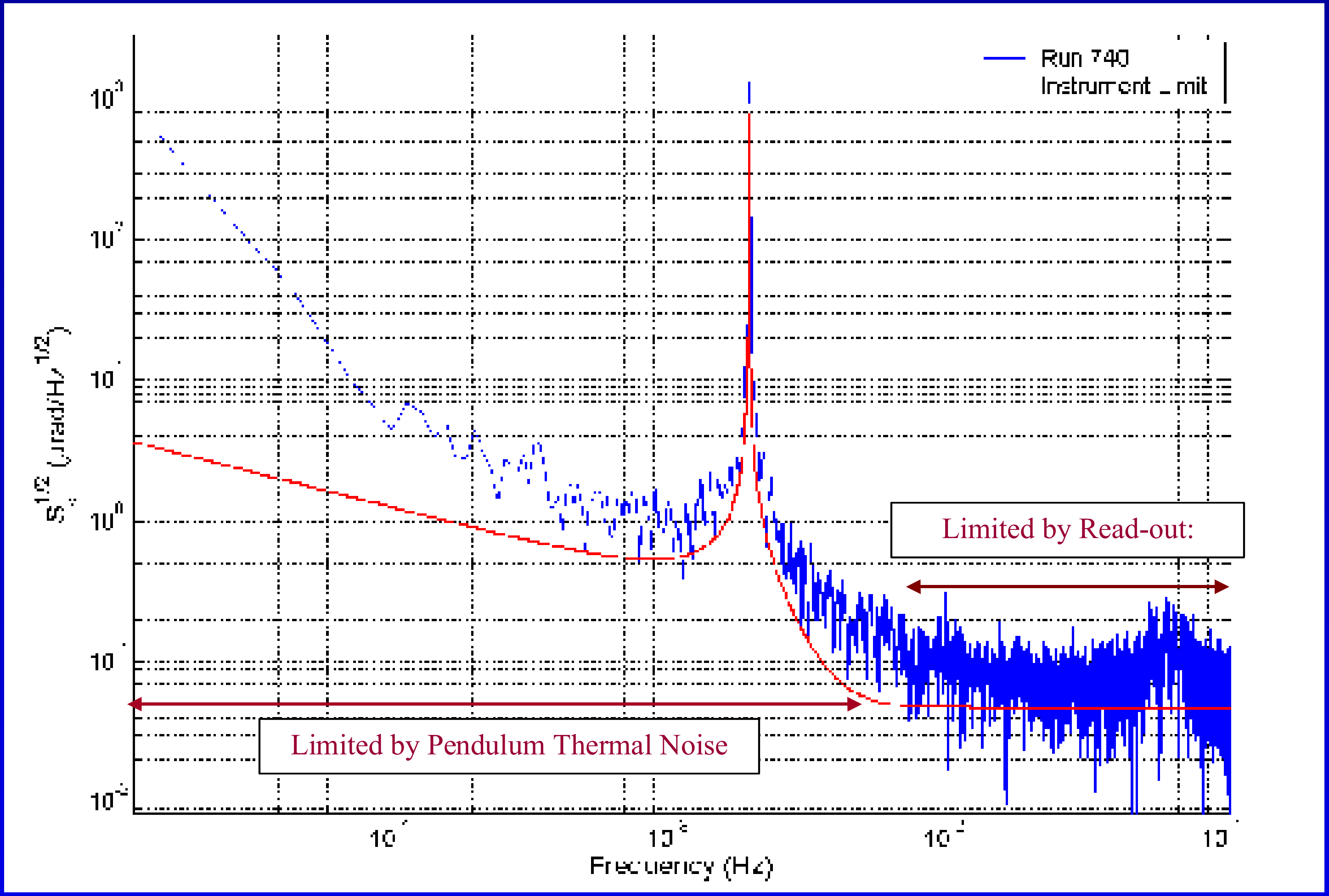


Hardware Upgrades in 2004



Plus ... bare tungsten fiber, Gold coated torsion member and stronger turbo-pump

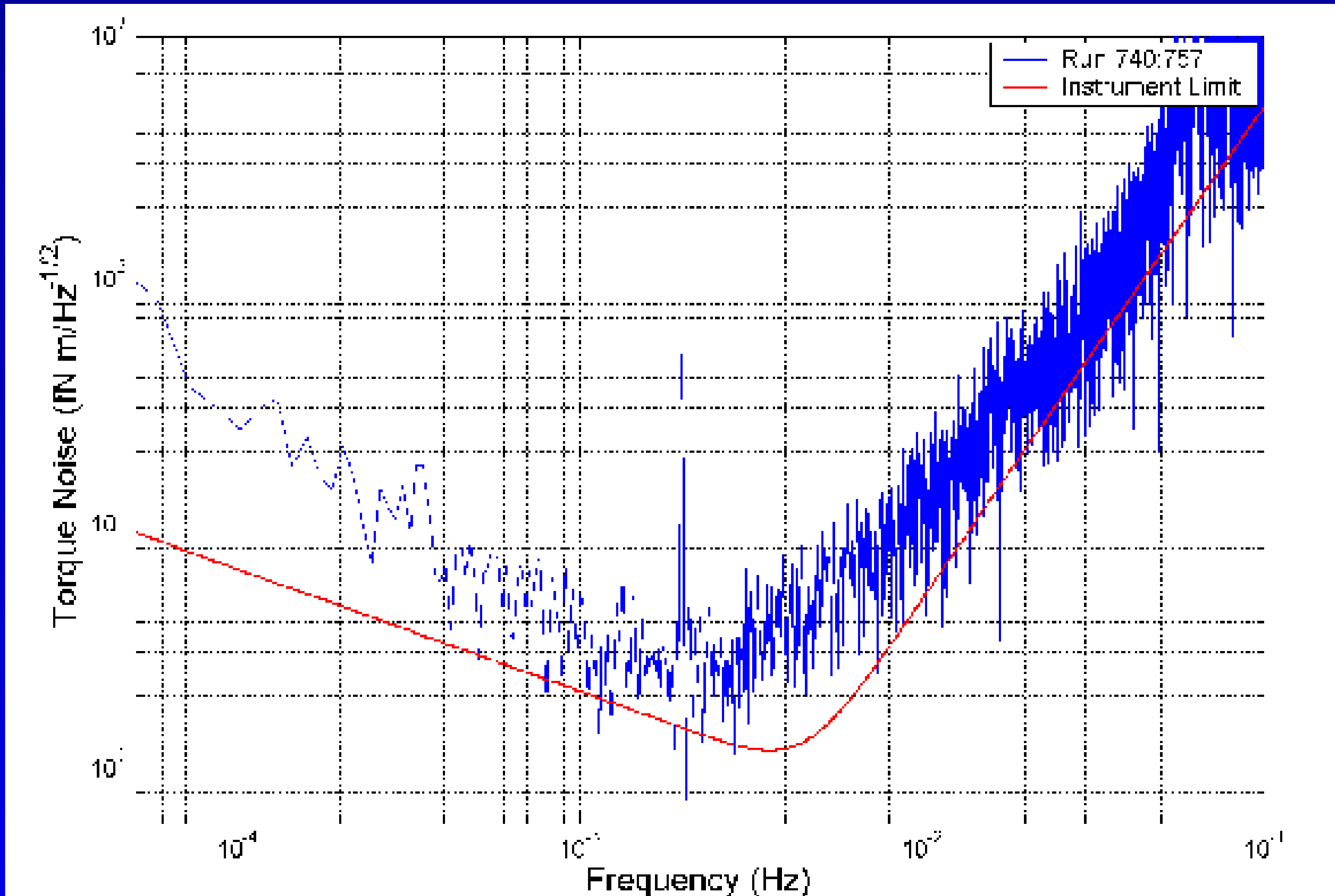
Torsion Pendulum Performances



Typical Torsional Angular Noise Spectrum

- Approaching pendulum thermal noise above 0.2 mHz
- Dominated by temperature stability at low frequencies

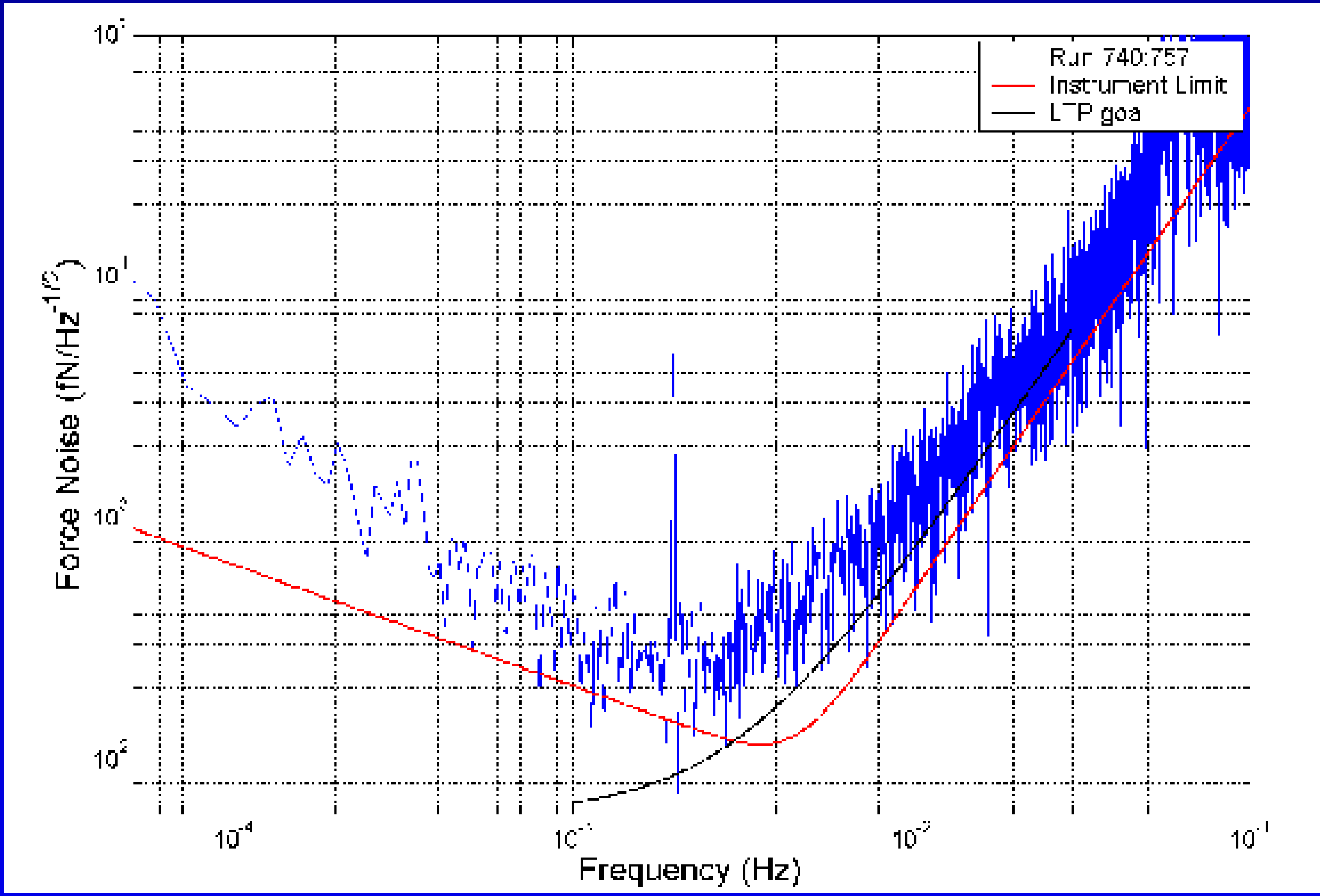
Torque noise measurements:



Torque noise calculated from angular noise and pendulum transfer function

- torque noise below 10 fN m $Hz^{-1/2}$ (0.35mHz - 9 mHz)
- minimum noise at 2mHz: 3fN m $Hz^{-1/2}$

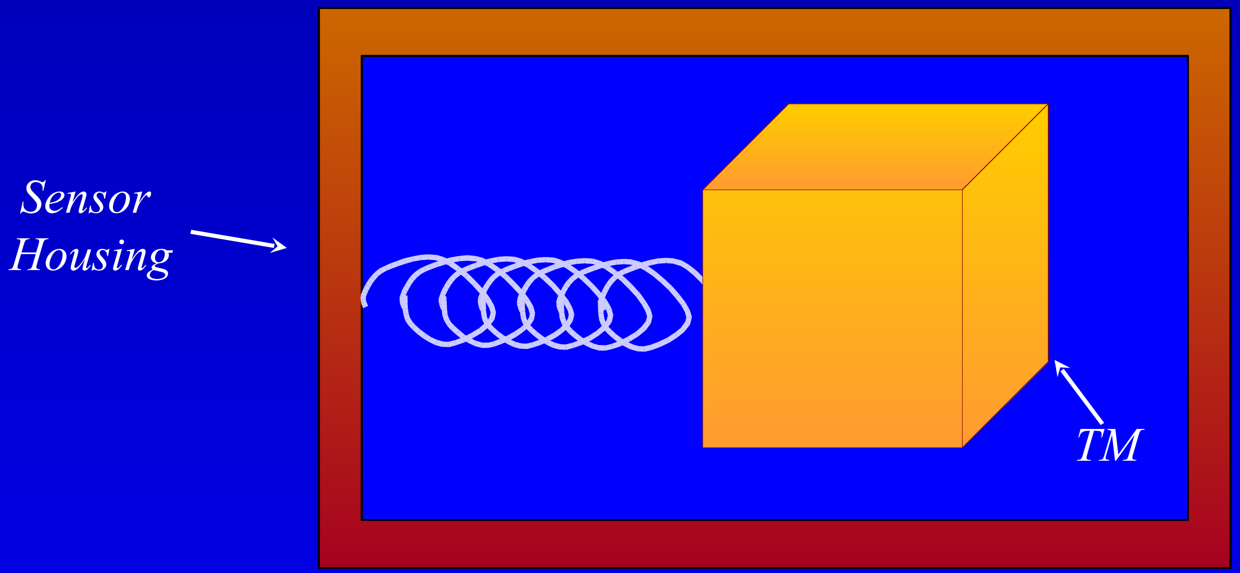
Force noise measurements:



- most stringent torque-force conversion (armlength ≈ 10 mm)
- roughly factor 5 above LTP goal at 1mHz (assuming 2kg TM)
- minimum: 250 fN Hz$^{-1/2}$ (1-3 mHz)

Sensor-Test Mass Stiffness measurements:

- Search for all sources of force gradients or spring-like coupling between sensor and TM, measure overall coupling
- Major contributions given by Sensing Bias and TM charge



- sources of translational stiffness typically also produce rotational stiffness

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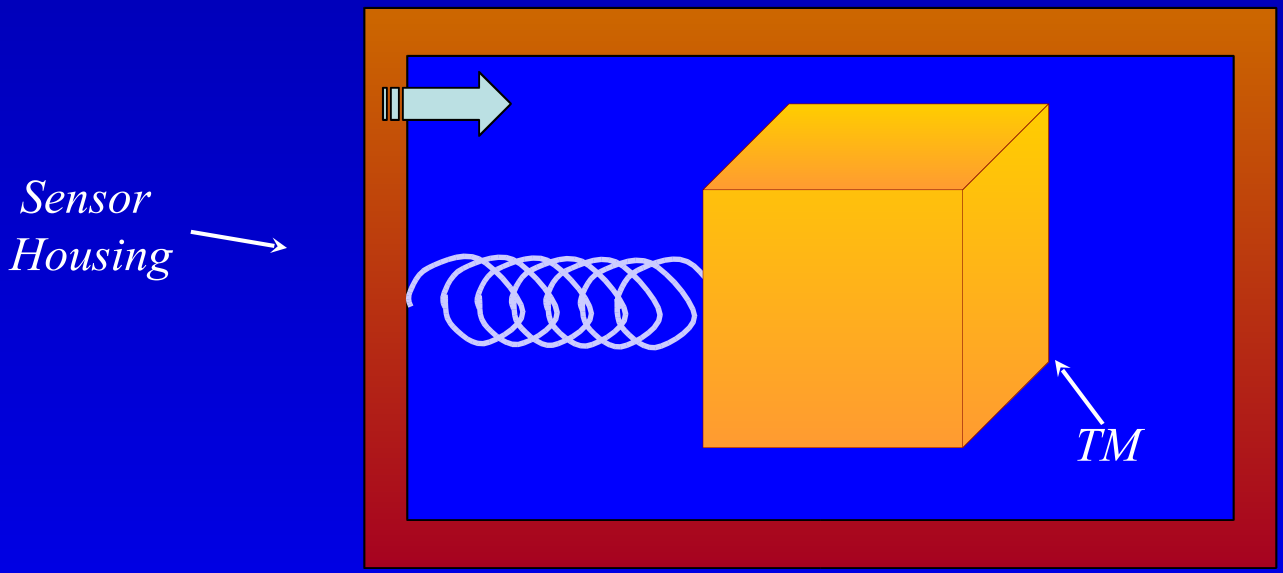

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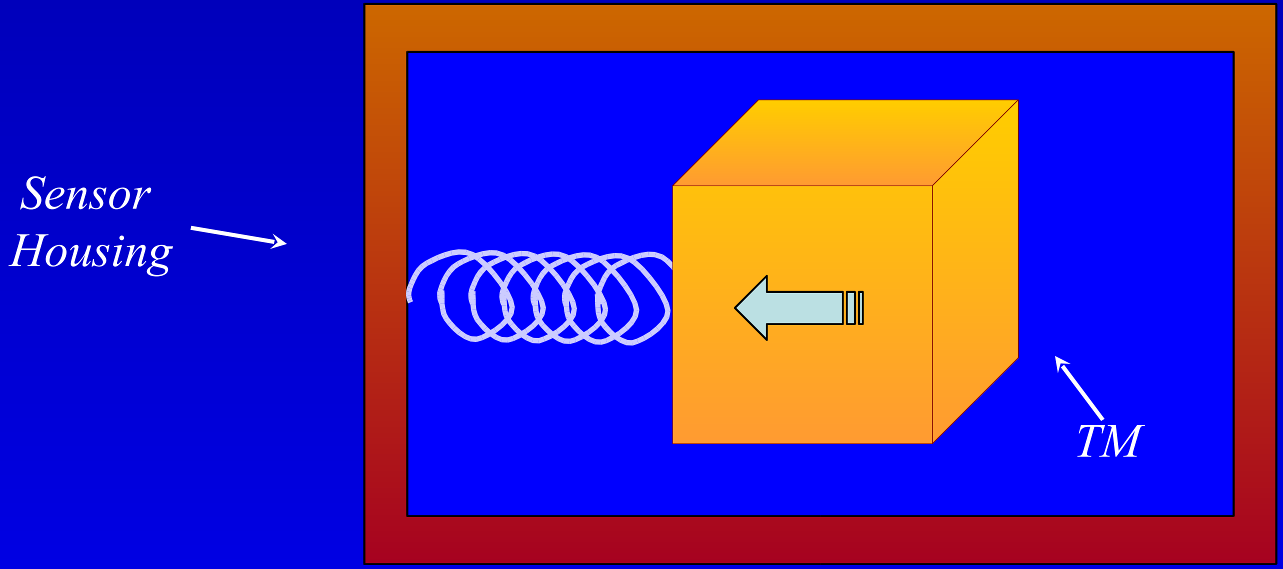
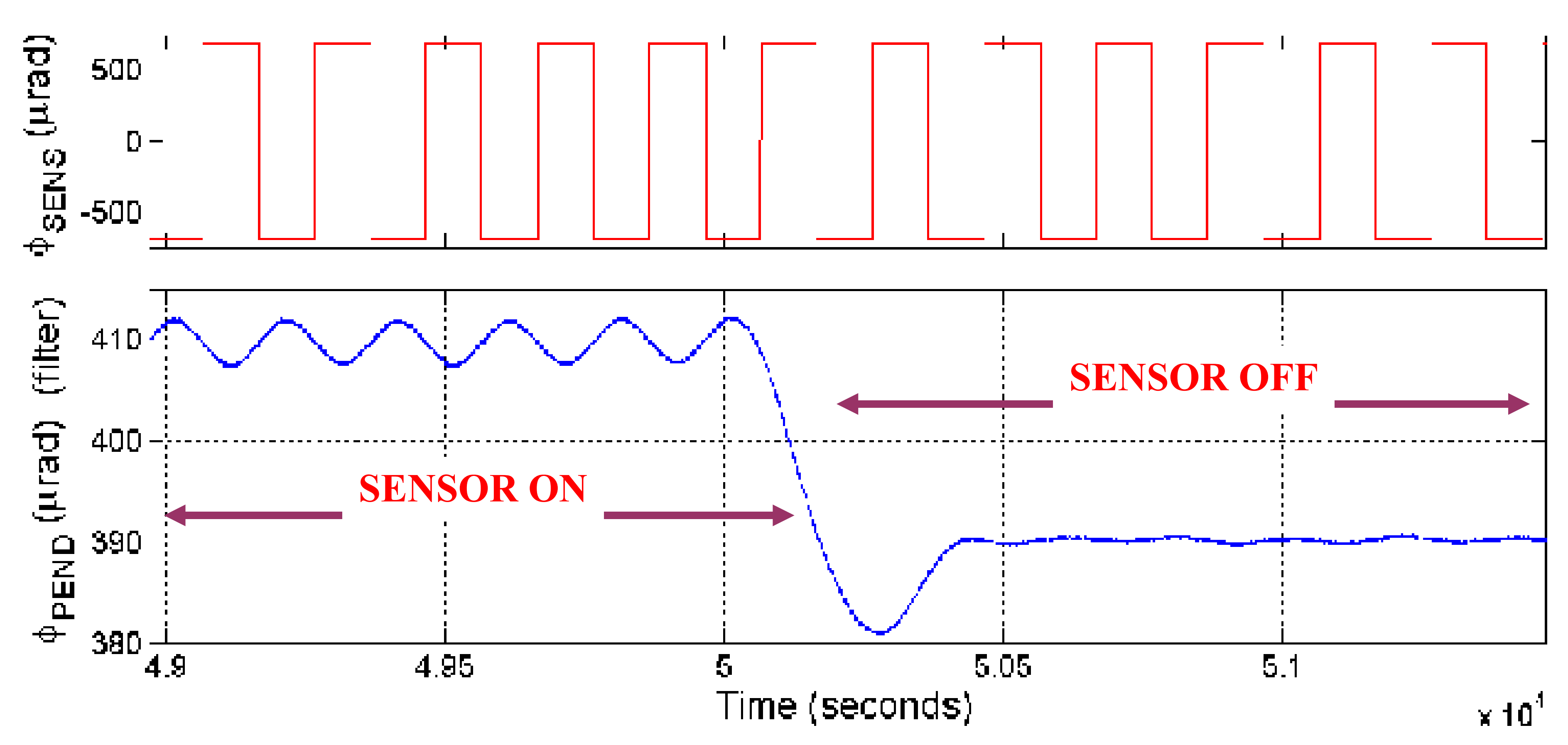


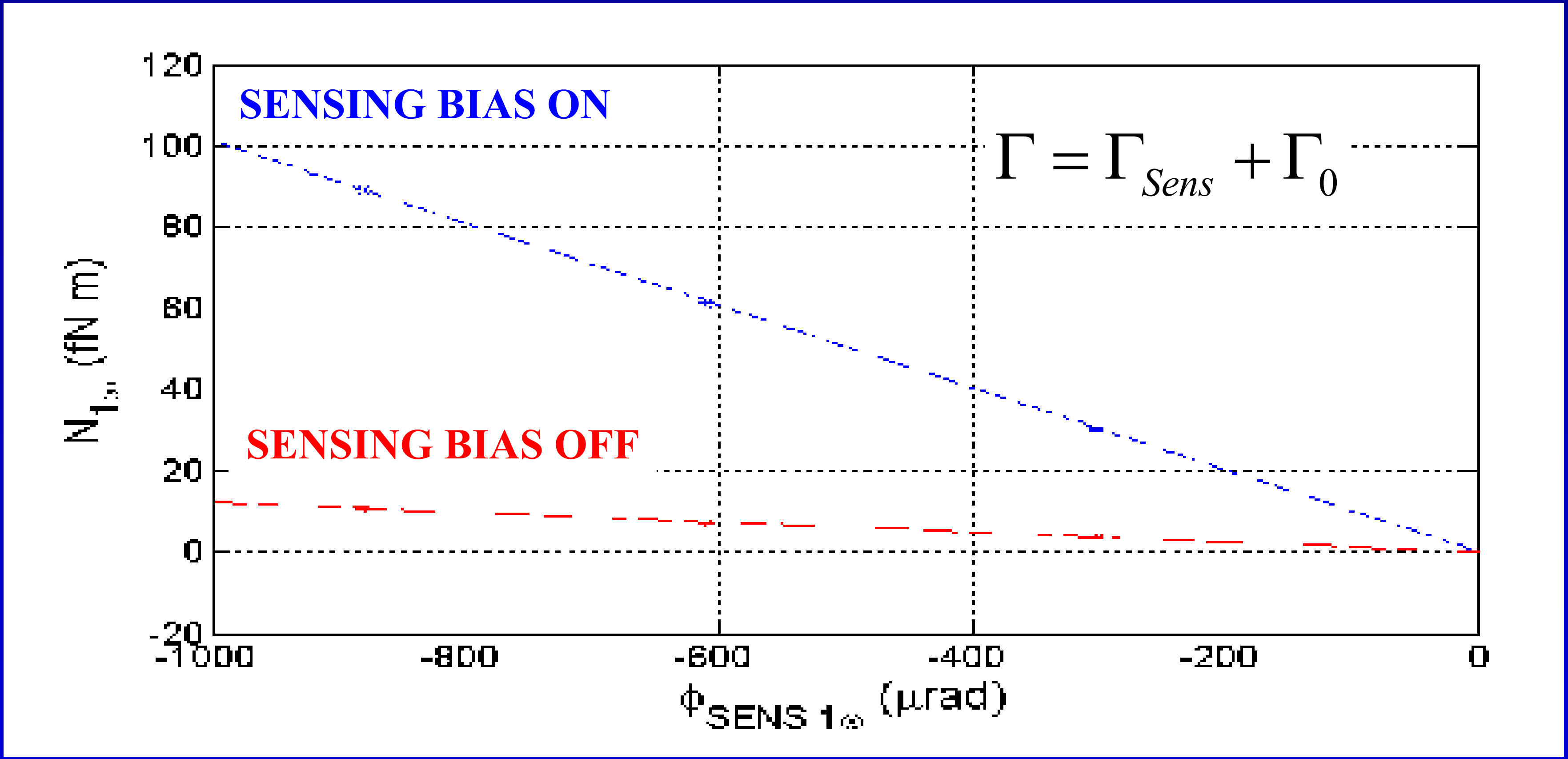
- sources of translational stiffness produce also rotational stiffness

- Coherent torque excited by square wave oscillation of sensor rotation angle, using a rotational motorized stage

- produce a square wave torque proportional to the stiffness

$$N(t) = -\Gamma \cdot \Delta\varphi(t)$$





- Sensing Stiffness Γ_{SENS} = - 89.2 ± .5 pN m / rad

  consistent with previously measured value

- Extra stiffness Γ_0 = - 12.0 ± .3 pN m / rad

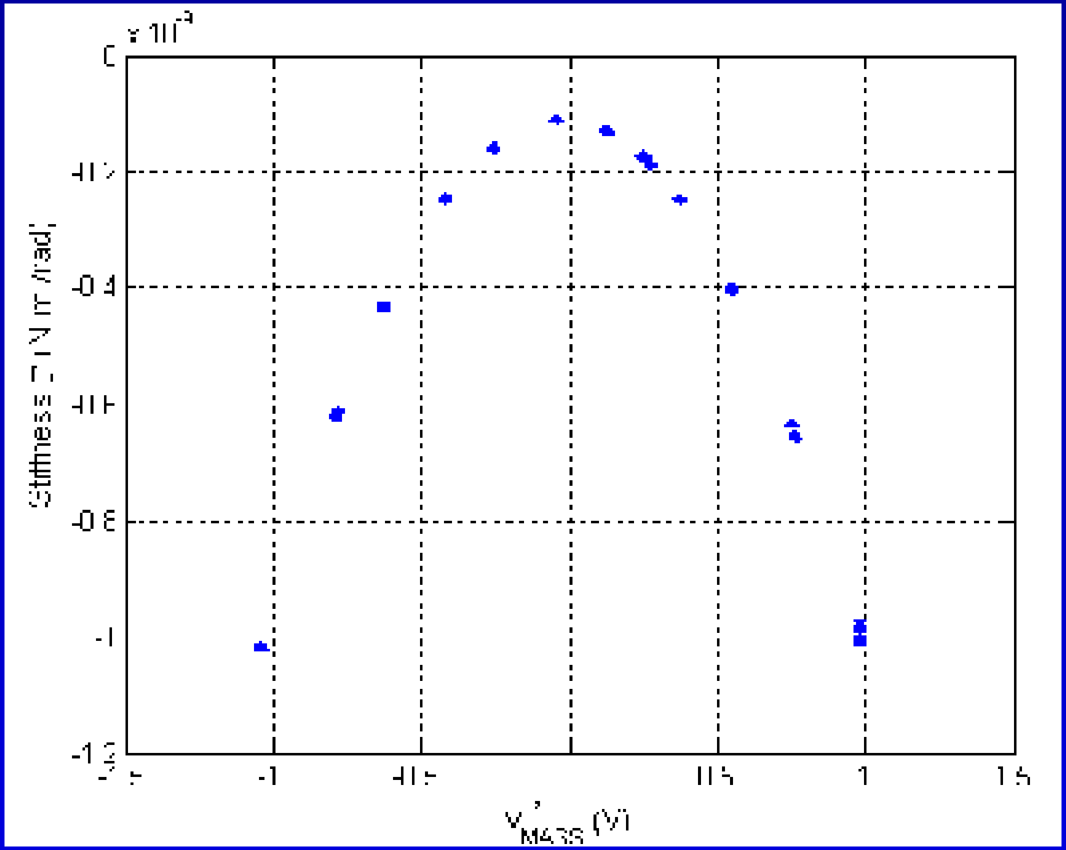
  could be explained by ***115 mV*** RMS patch voltages
  or residual of trans-twist interaction

Confirmation of charge – stiffness model

$$\Gamma_{tot} = (\Gamma_{sens} + \Gamma_0) - \frac{1}{2}\left(\sum_i \frac{\partial^2 C}{\partial \phi^2}\right)(V_M - V_{OFF})^2$$

- developed a technique for measuring TM voltage drop to ground

- optical fiber with UV light installed for charge management (with Imperial College - London)

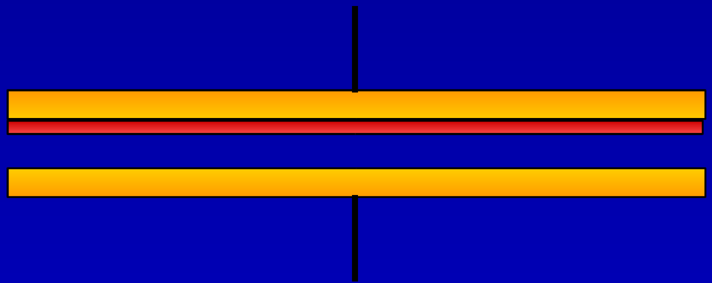


Results:

$$\Gamma_{SENS} + \Gamma_0 = -111.2 \pm .2 \text{ pN m /rad}$$ [sensor plus excess stiffness]

- $\sum_i \frac{\partial^2 C}{\partial \phi^2} = 1.84 \pm .001 \text{ nF/rad}^2$ [ANSYS prediction: 1.77 nF/rad², Diana Shaul]
- $V_{OFF} = -20.2 \pm .3 \text{ mV}$ [likely a patch charge effect between 4 electrodes used in charge measurement and rest of sensor]

Measurement of dielectric loss angle:



Lossy layer on sensing electrodes

$$C = C_0(1 - i\delta)$$

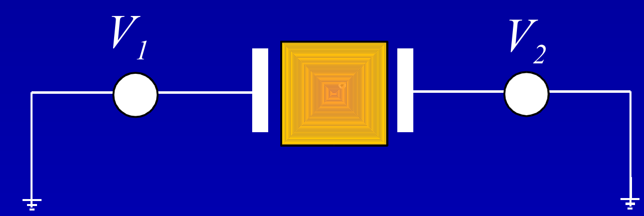
…adsorbed dipole layer, electron hopping among work-function minima…

- Dielectric losses contribute to voltage thermal noise
- Mixing with DC voltages produces Force Noise

$$S_f = 4k_B T C_0 G^2 \frac{\delta}{\omega}$$

- Pendulum ringdown measurements to date have proved irreproducibile at a level which prevents extraction of δ better than 10^{-4}

Measurement of dielectric losses: new direct measurement technique

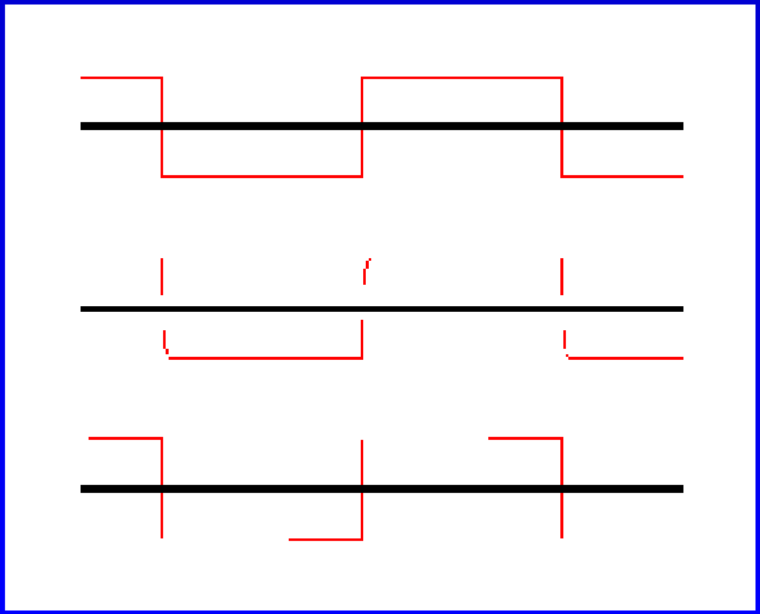


- Direct measurement technique:
  - A square wave voltage passing through the capacitor feels a delay created by lossy elements

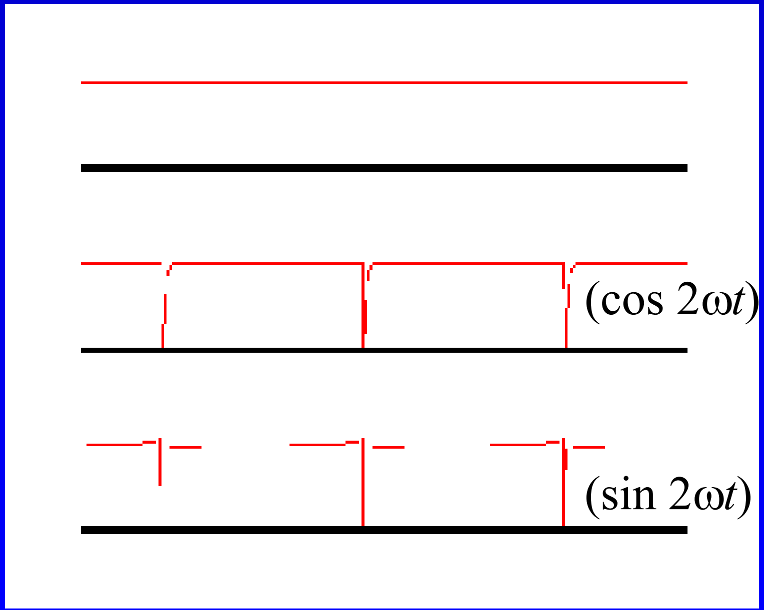
$$C = C_0(1 - i\delta)$$

- Application of perfect square wave yields constant force *($F \sim V^2$)*
- Any lossy element creates delays and thus force transients

Electrode voltage:



Force



No losses

Ohmic delay

δ constant

Measurement of dielectric losses: the measurement technique

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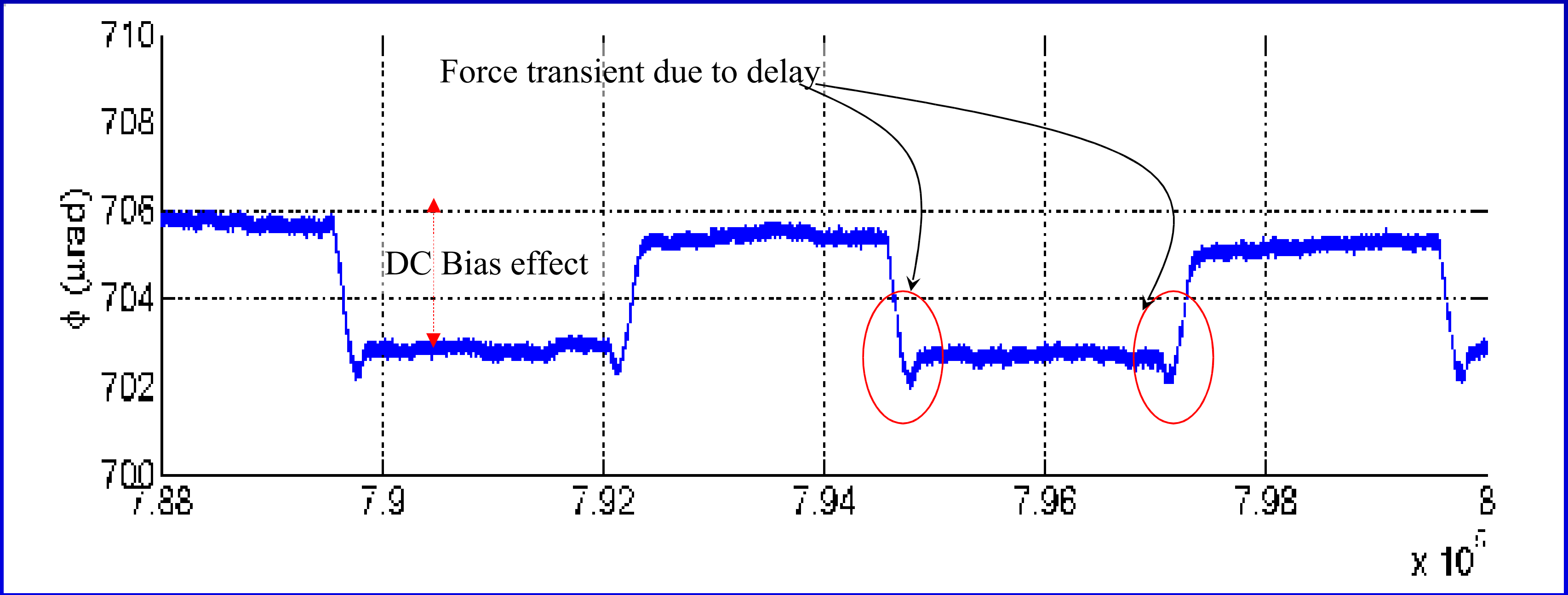
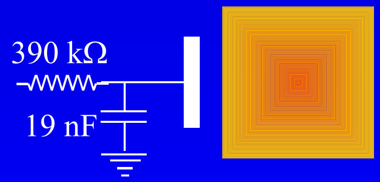


Application through
an ohmic delay
($\tau \approx 7$ ms, $\delta \approx 2\ 10^{-5}$)



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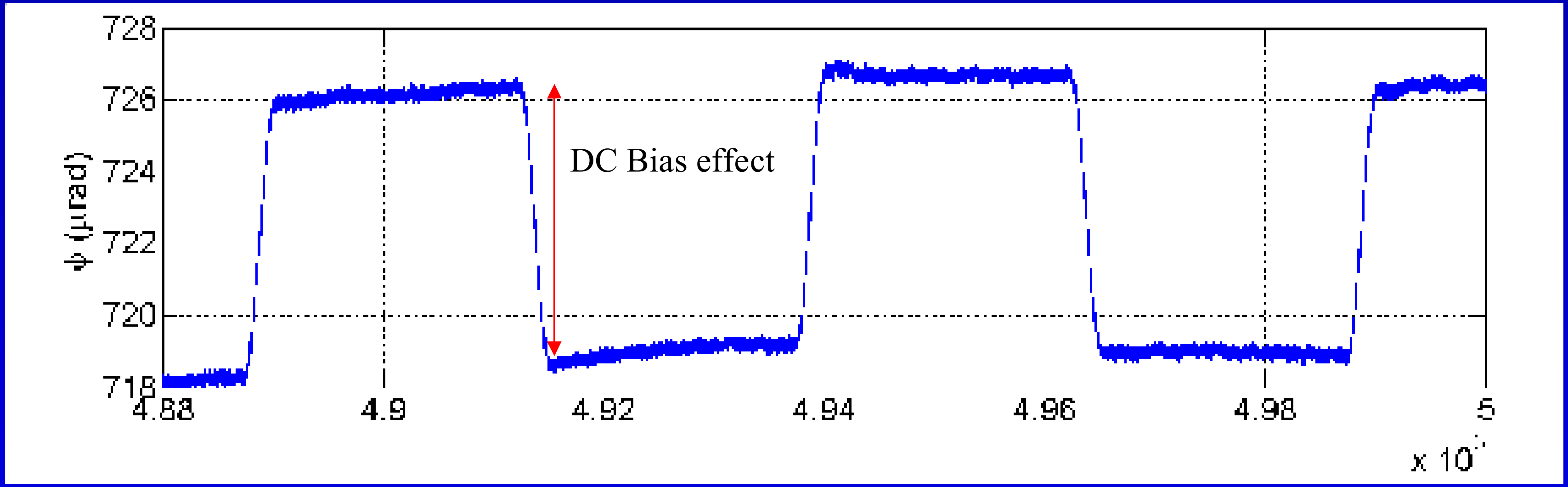
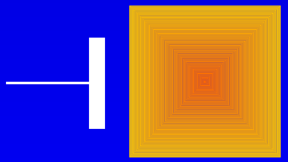
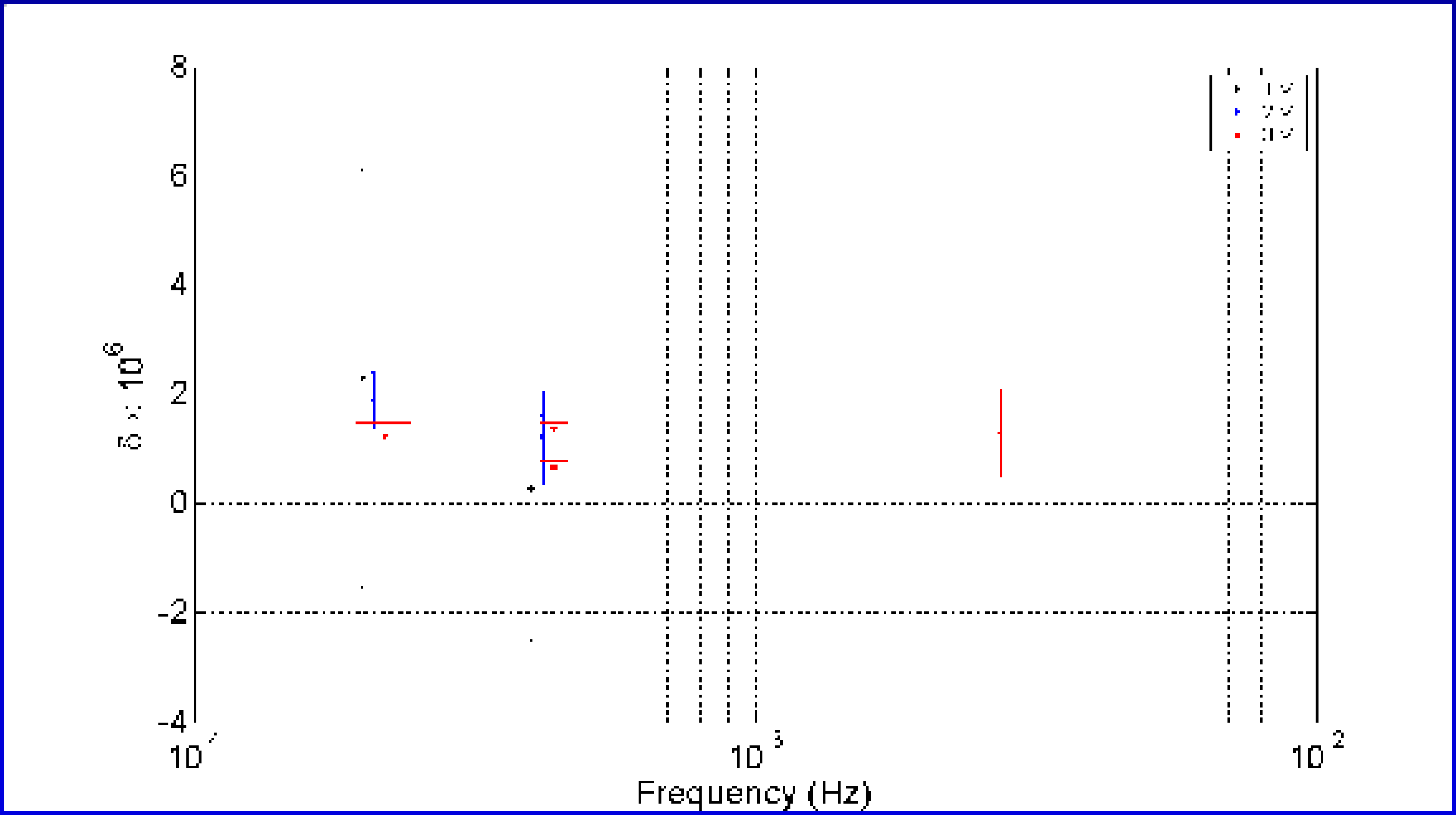


Direct application
(*f* = .4 mHz)



Measurement of dielectric losses: preliminary results

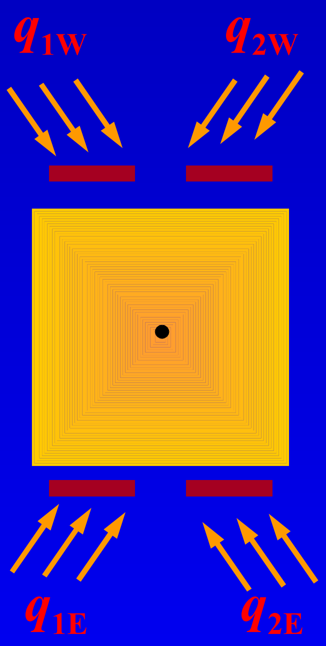


- very sensitive (can resolve $\delta \approx 10^{-6}$)
- preliminary measurements indicate δ of order 10^{-6} (LTP / LISA goal 10^{-5})
- calibrations performed with Ohmic losses
- need to also calibrate for non-Ohmic loss angles (δ independent of frequency), ... currently in progress

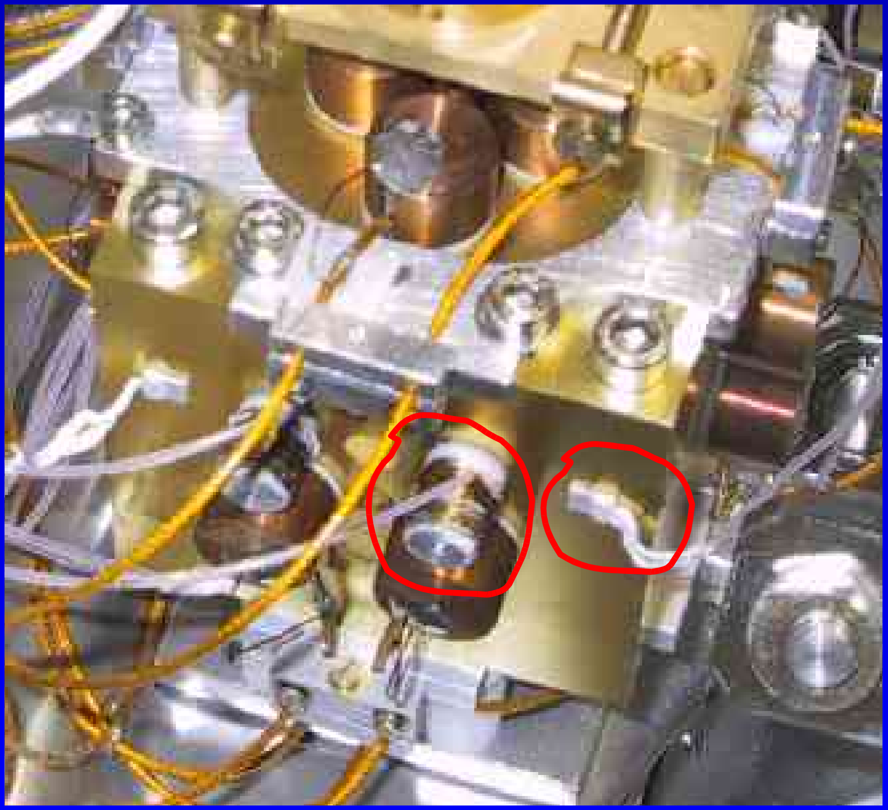
Thermal Gradient Related Effects:

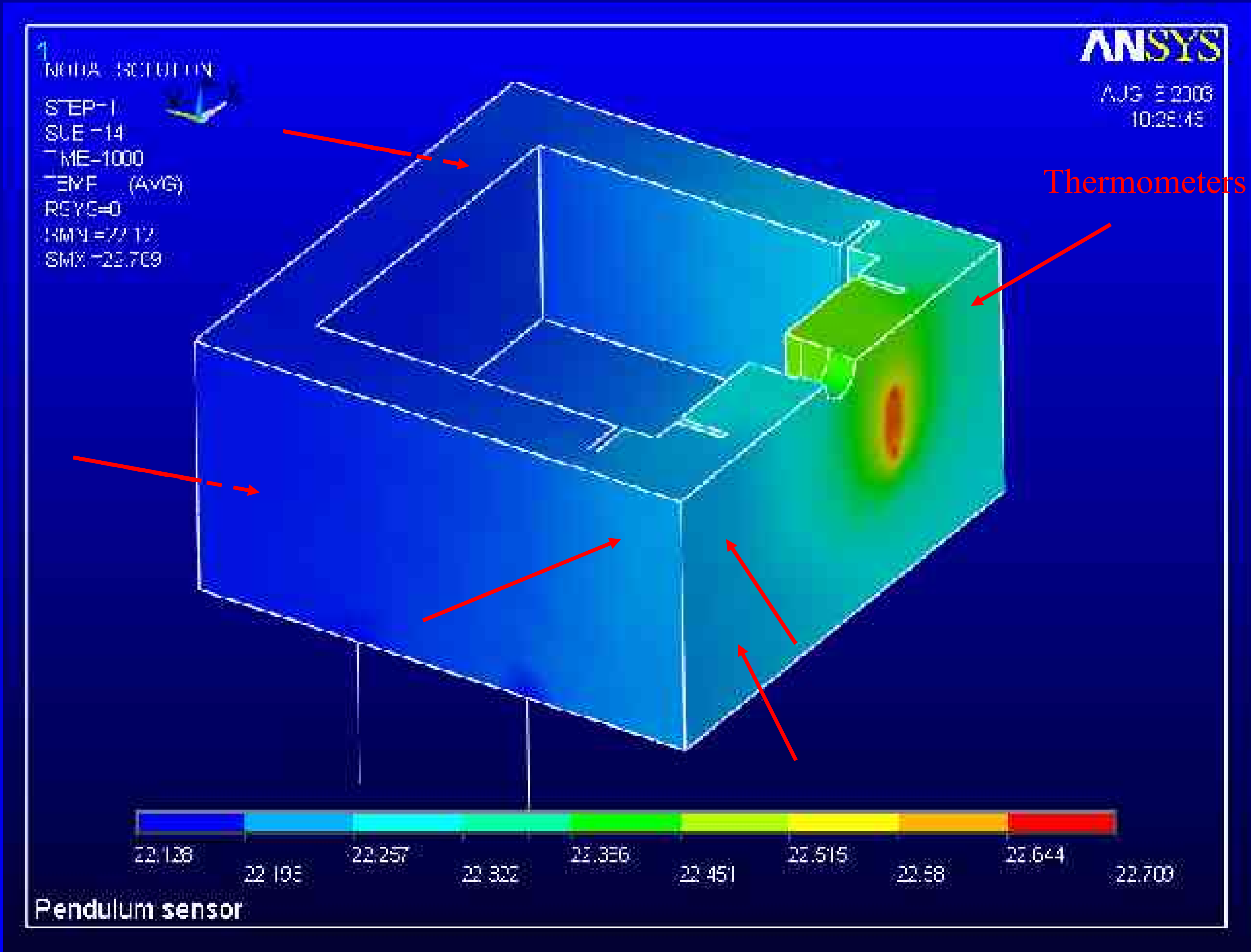
- Search for temperature gradient induced torques in excess of that expected for radiometric and radiation pressure effects

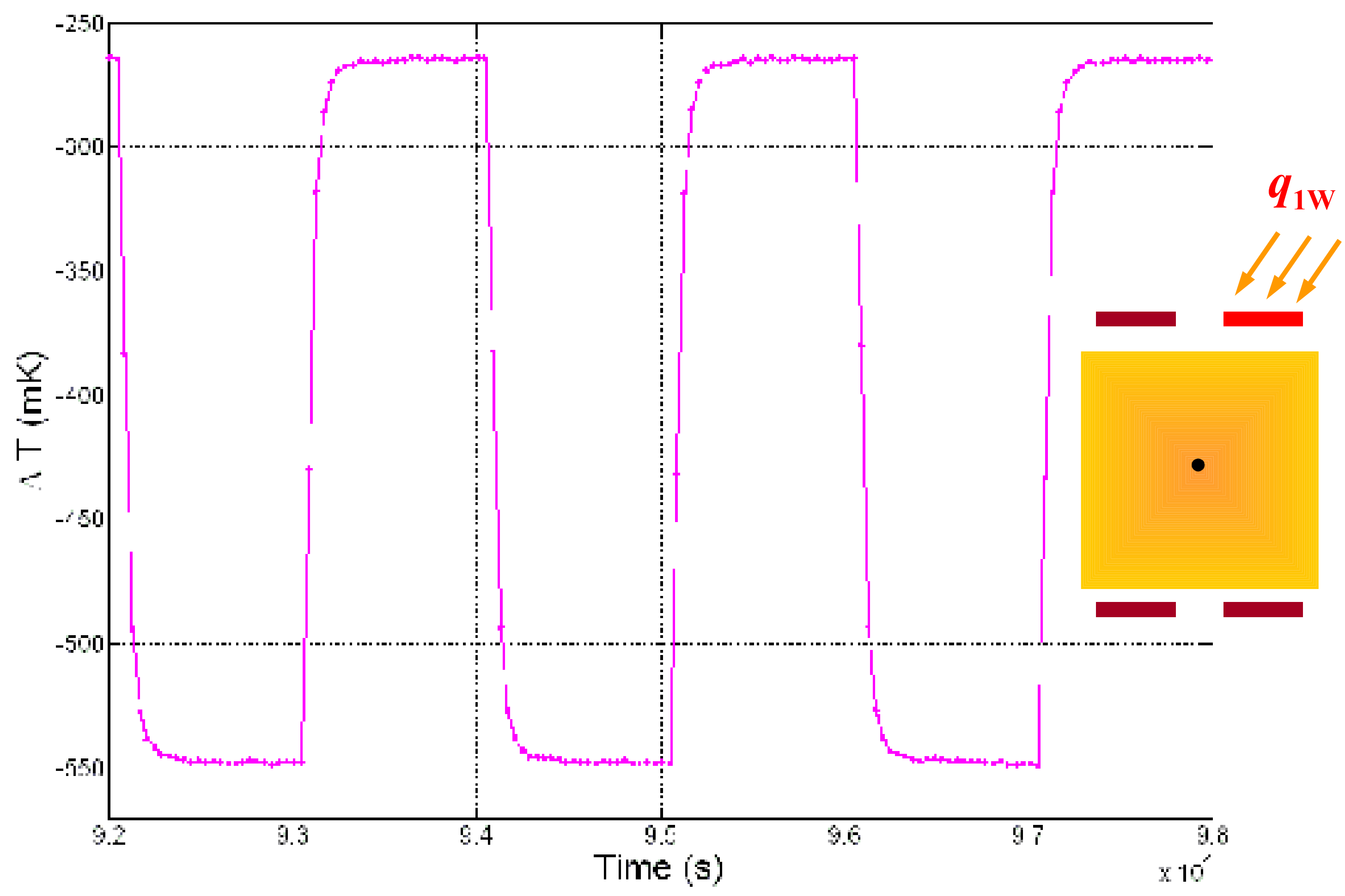
- Outgassing effect difficult to predict (virtual leaks, impurities…)



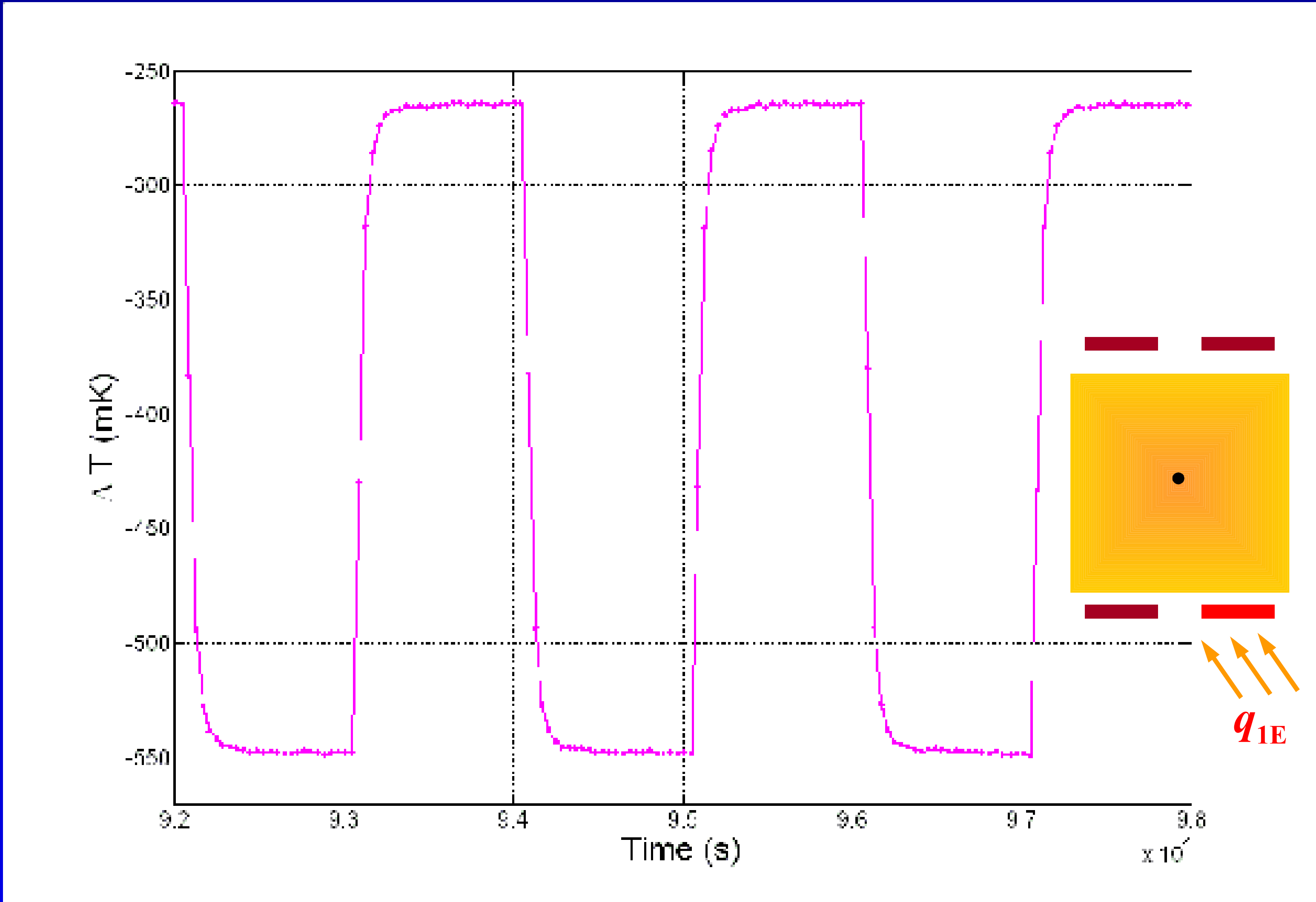
4 independent electrical heaters to apply rotational thermal gradients




ANSYS
1
NODAL SOLUTION
STEP=1
SUB =14
TIME=1000
TEMP (AVG)
RSYS=0
SMX =22.709
Thermometers
22.128
22.193
22.257
22.322
22.386
22.451
22.515
22.58
22.644
22.709
Pendulum sensor



- Alternate 0.2Watts on opposed electrodes (1W-1E) @ 0.5mHz
- Temperature measured in vicinity of heaters
- $T_{ave} \approx 22°C$



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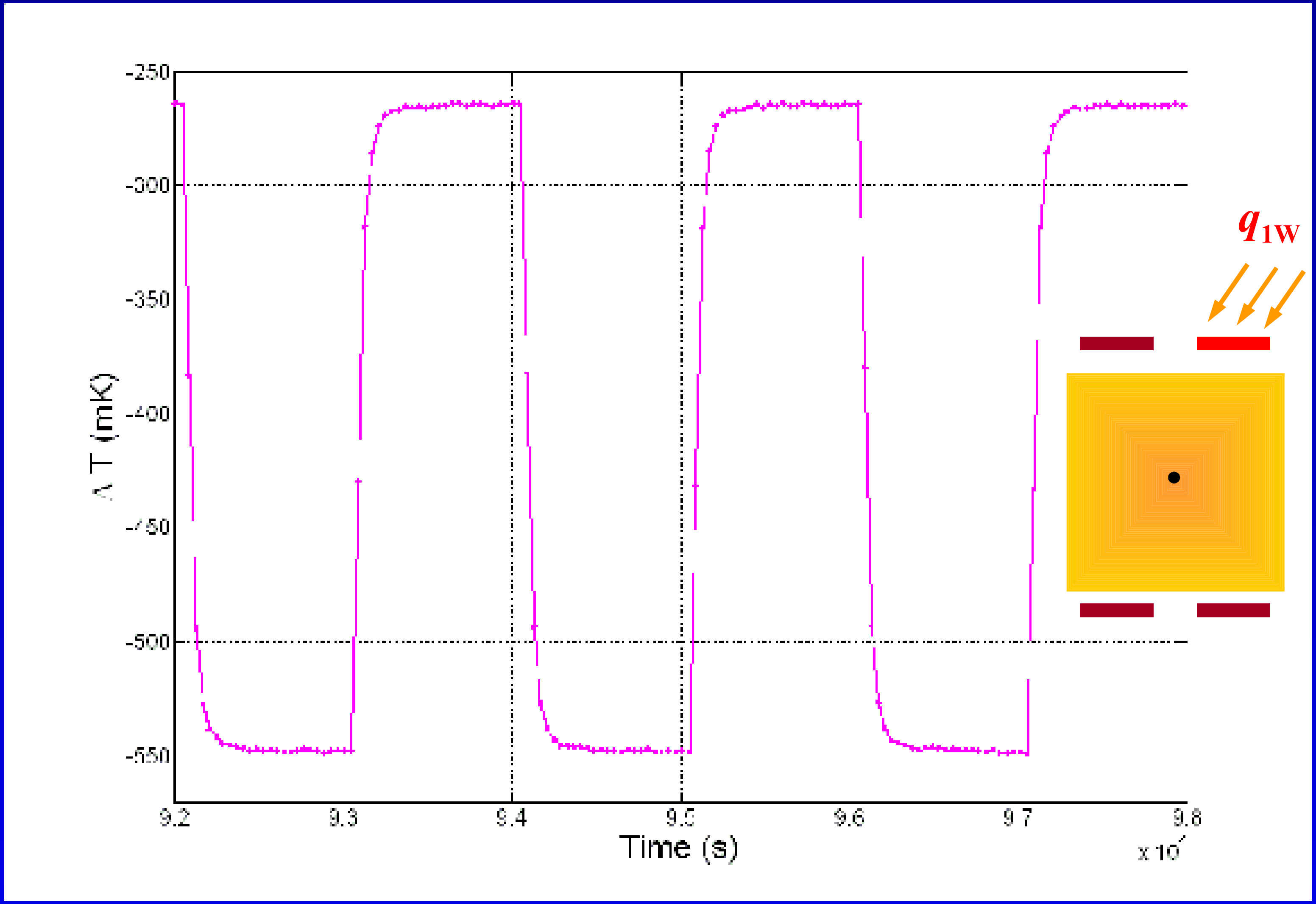

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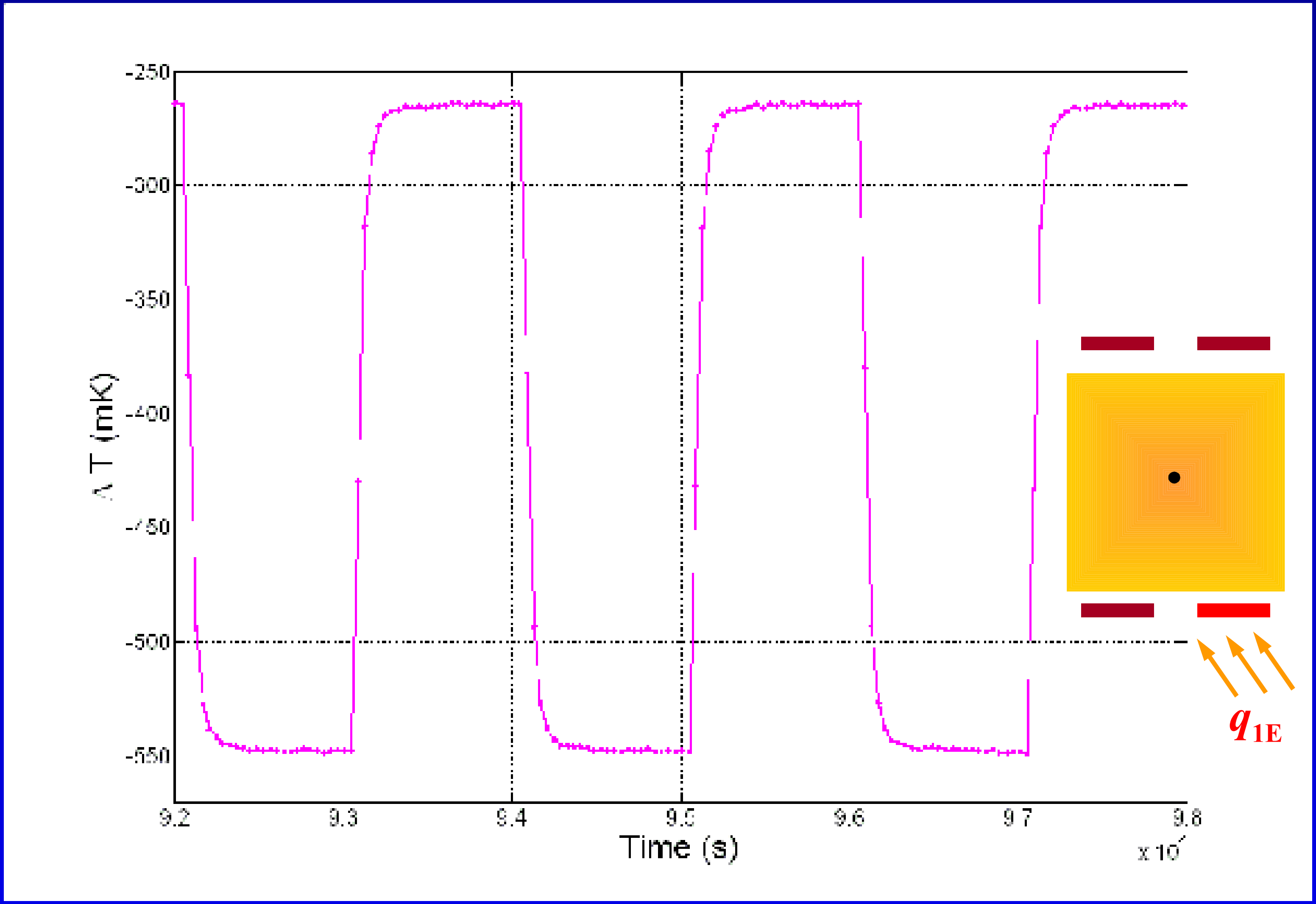

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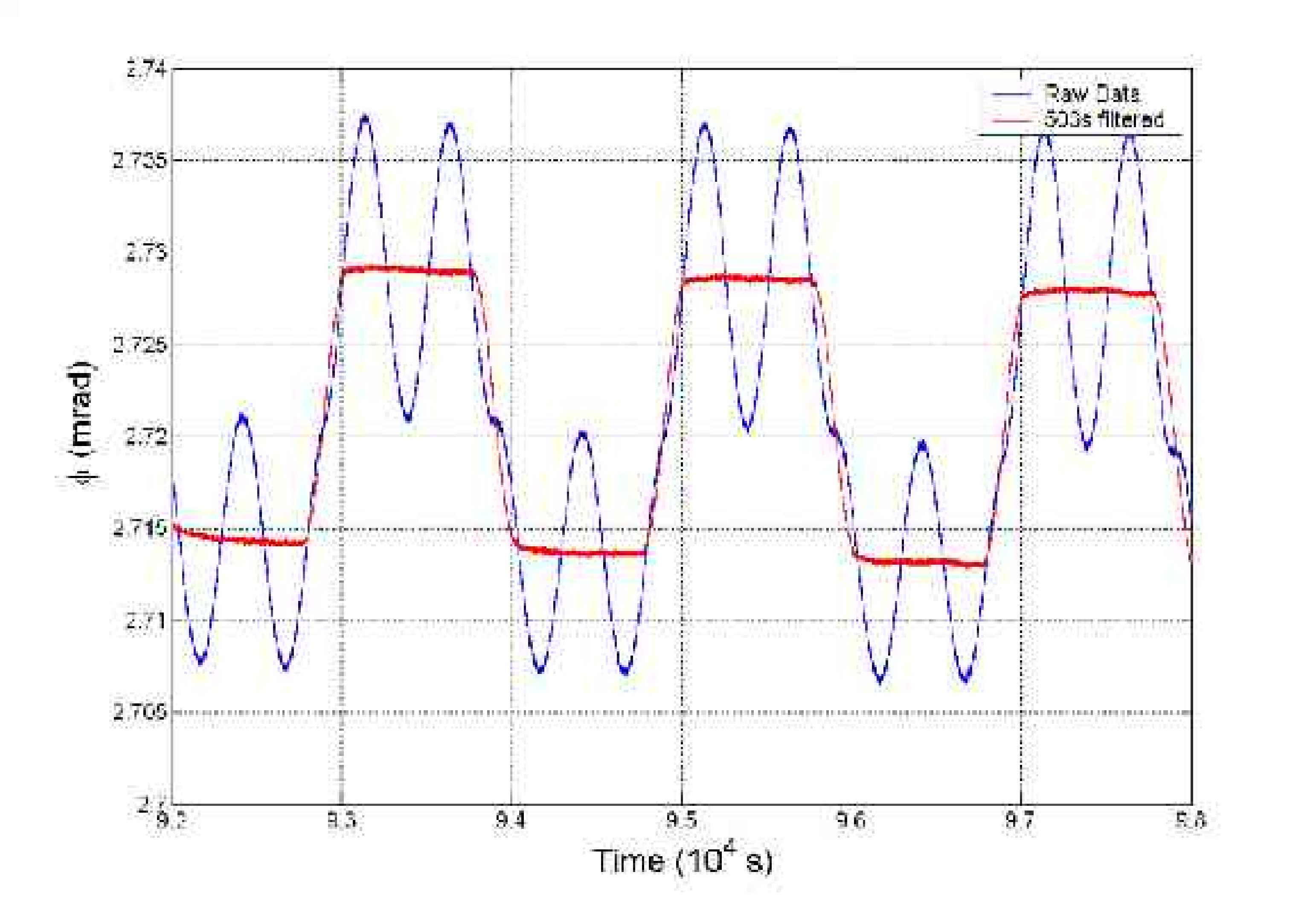
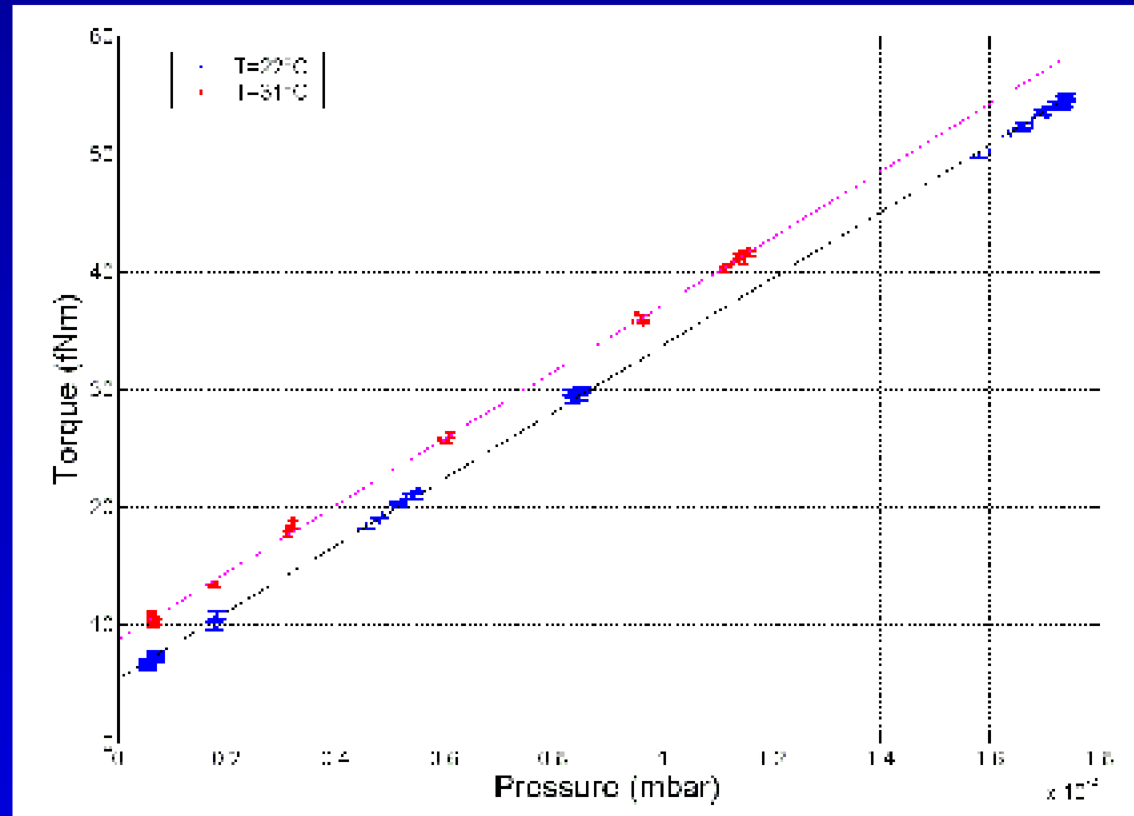


- Pendulum coherent response:
  equilibrium position changes every 1000s
- Vacuum chamber Pressure ≈ 5 10^{-8} mbar

Thermal gradient effects as function of pressure and temperature

Measurement of induced torque as function of pressure and temperature

$$\left\{ \begin{array}{l} N_{radiom} \propto P_{out} \dfrac{\Delta T_{eff}}{T_s} \\ N_{outgas} \propto \dfrac{\Delta T_{eff}}{T_s^{\,2}} \Theta Q_{outgas} \\ N_{rad\ press} \propto T_s^3 \Delta T_{eff} \end{array} \right.$$



Preliminary results:

- measured torque is consistent with radiometric+radiation pressure effects
  (factor ≈ 2 uncertainty in effective temperature gradient)
- no evidence of huge temperature dependent outgassing effects!

Investigation needed:

- pressure and temperature interpretation
- applied effective thermal gradient modeling

Summary of main results:

- More stringent upper limits to stray forces (extending to lower frequencies)
- Measured Overall Spring-like coupling
- New technique for measuring dielectric loss angle
- Thermal gradients induced effects under investigation ……

- Charge measurement technique successfully demonstrated
- Charge Control based on UV light demonstrated
- Stray DC bias voltage measurement and compensation improved