The activities of micro-force measurement below 10 mN in Center for Measurement Standards

Sheng-Jui Chen and Sheau-Shi Pan

With contribution from :

Ya-Ko Chih, Chung-Lin Wu, Fu-Lung Pan, Chin-Fen Tuan and Yi-Ching Lin

Center for Measurement Standards (CMS), Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan, R.O.C.

Outlines

- 1. CMS in ITRI
- 2. Force measurement below 1 N
- 3. Small force measurement schemes in CMS
  - 3-1. Torsion pendulum facility
  - 3-2. Flexure stage with electrostatic sensing and actuating
- 4.Summary

1.CMS in ITRI

- One of our main projects:

National Measurement Laboratory

Establish, maintain, and disseminate national measurement standards.

- **Electrical/Electromagnetic Measurement Laboratory**
- **Dimensional Measurement Laboratory**
- **Dynamic Engineering Measurement Laboratory**
- **Optical Radiation Measurement Laboratory**
- **Quality Engineering Department**
- **Mechanical Measurement Laboratory**
- **Flow & Energy Research Laboratory**
- **Medical & Chemistry Research Laboratory**

Mechanical Measurement Lab

National Measurement Standards in fields of:

Mass

Hardness

Force

Mass & Gravity (F=mg)

PTB

500 kN ~ 2 MN Built-up Machine (1996)

50 kN ~ 500 kN Built-up Machine (1987)

5 kN ~ 50 kN Deadweight Machine (1997)

500 N ~ 5 kN Deadweight Machine (1987)

1 N ~ 500 N Deadweight Machine (2003)

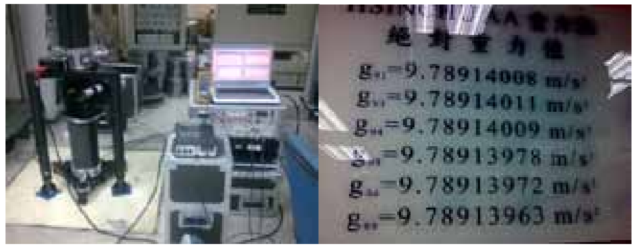
Pressure

Vacuum

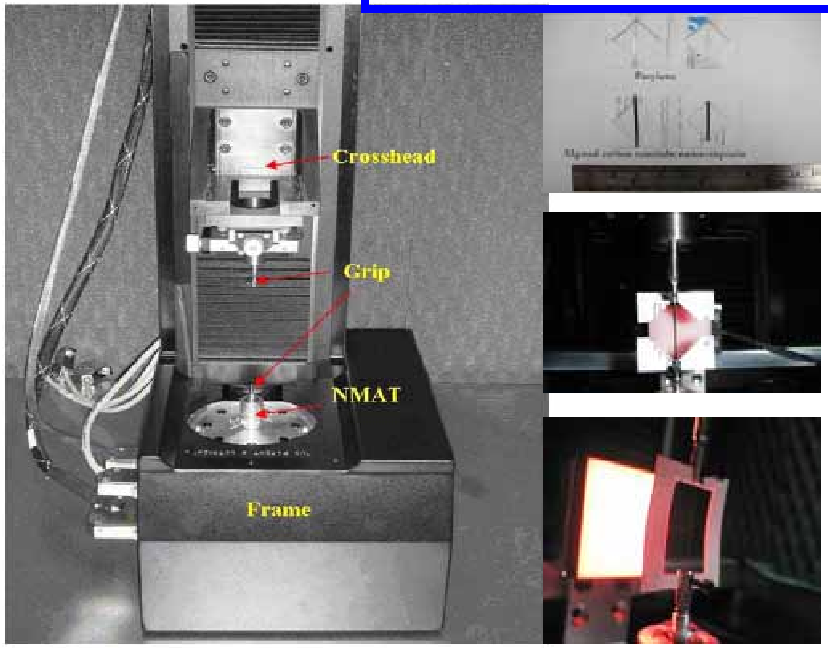
2.Force measurement below 1 N

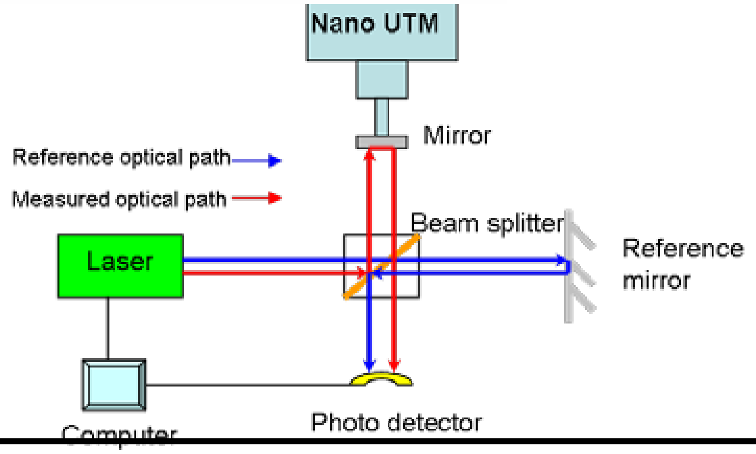
Nano Universal Testing Machine

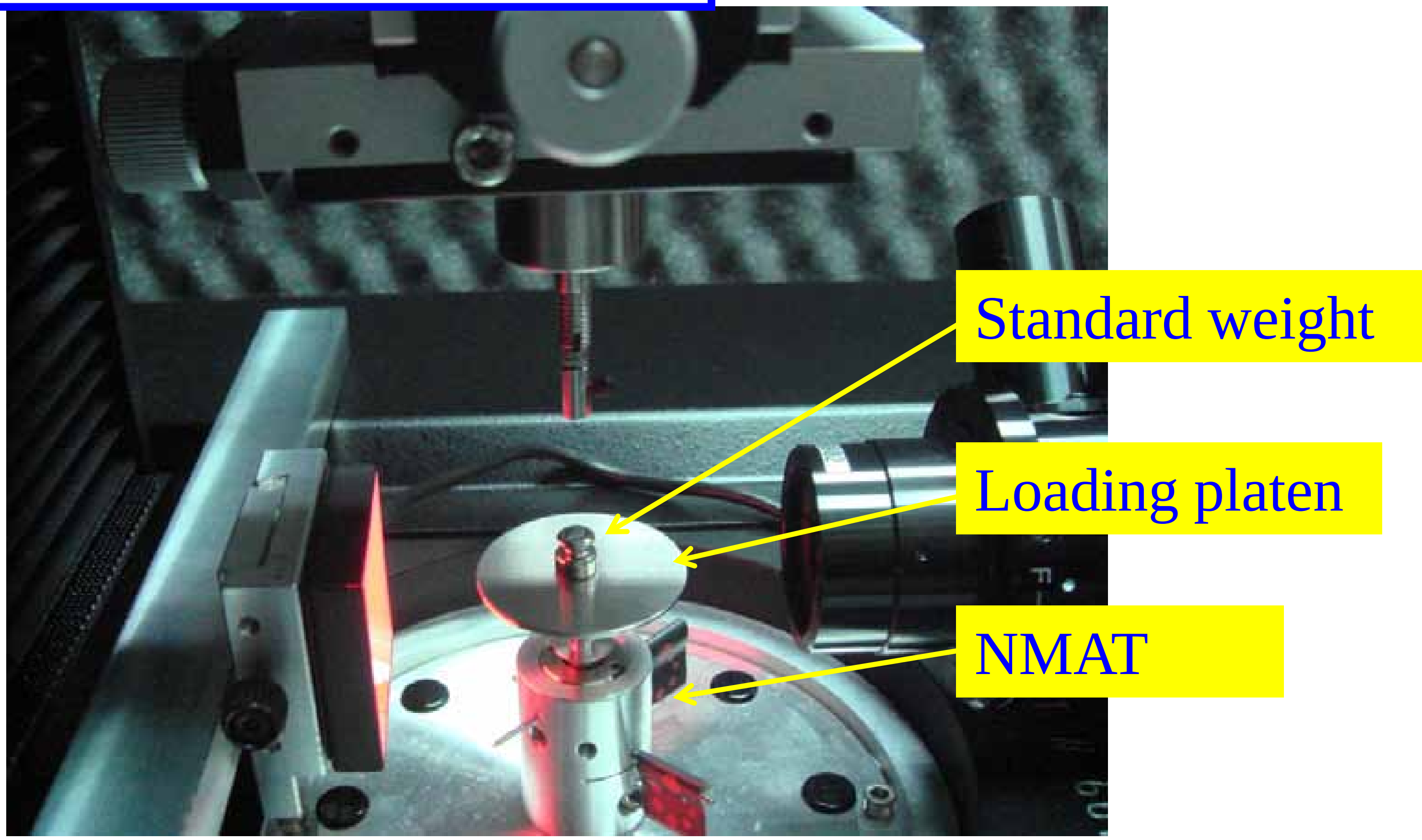
x



$F=mg$





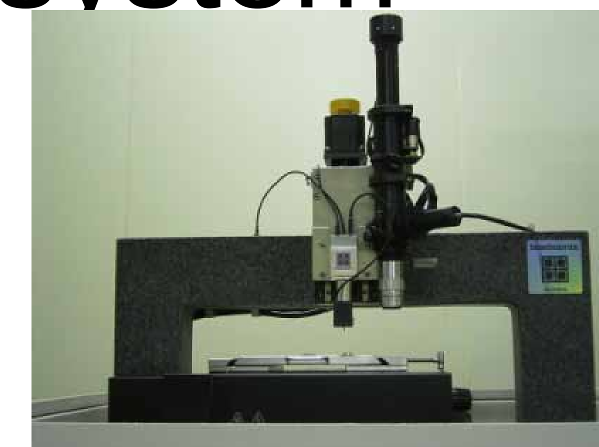


Force range: £ 500 mN
Extension range: £ 150 mm
Test material: spider silk, polymer material, thin film

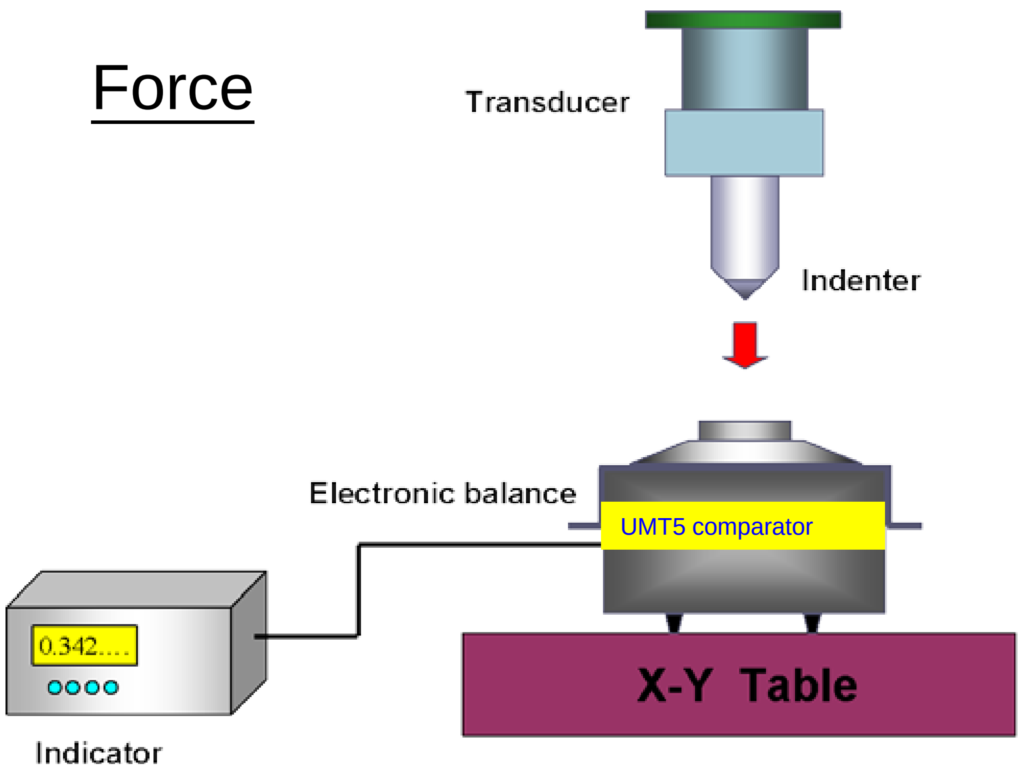
Force measurement below 1 N

Calibration of Nano-indentation system

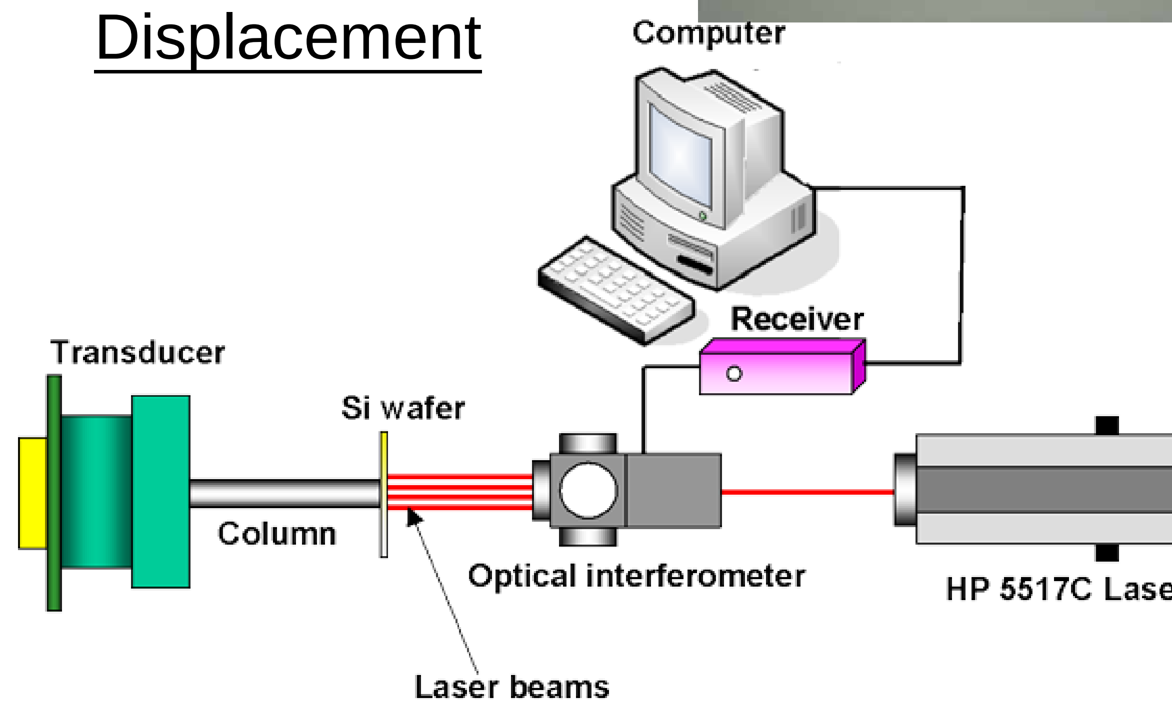
Force range: £ 10 mN
Indentation depth: £ 500 mm
Test material: Bulk material, Thin Film Specimen



Force

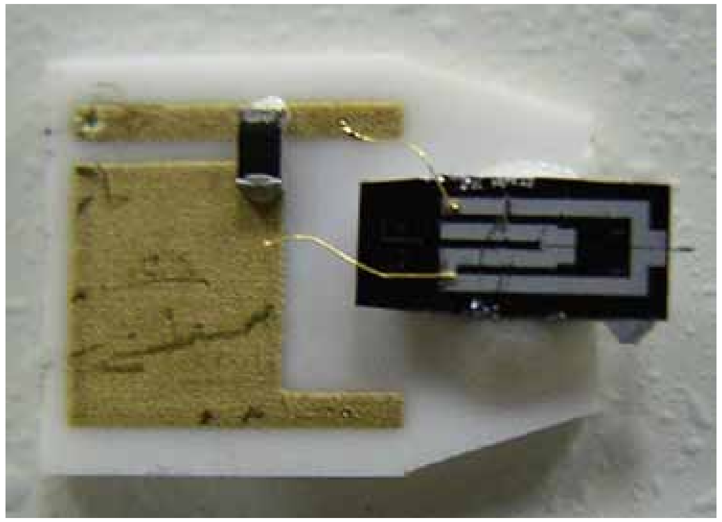


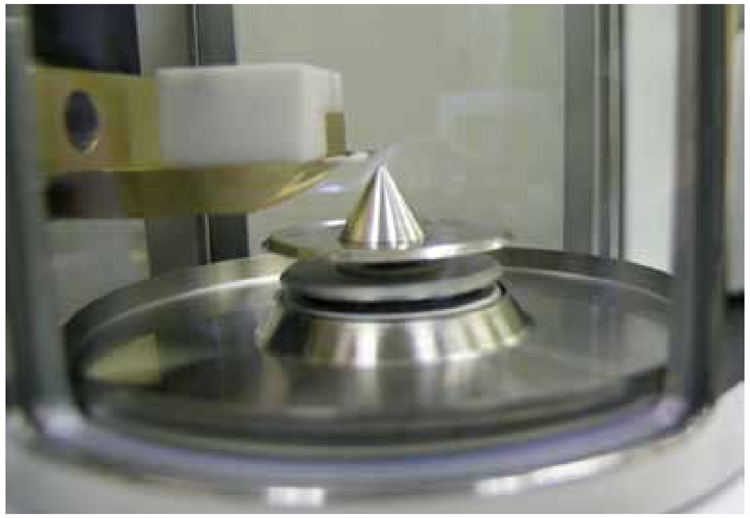
Displacement

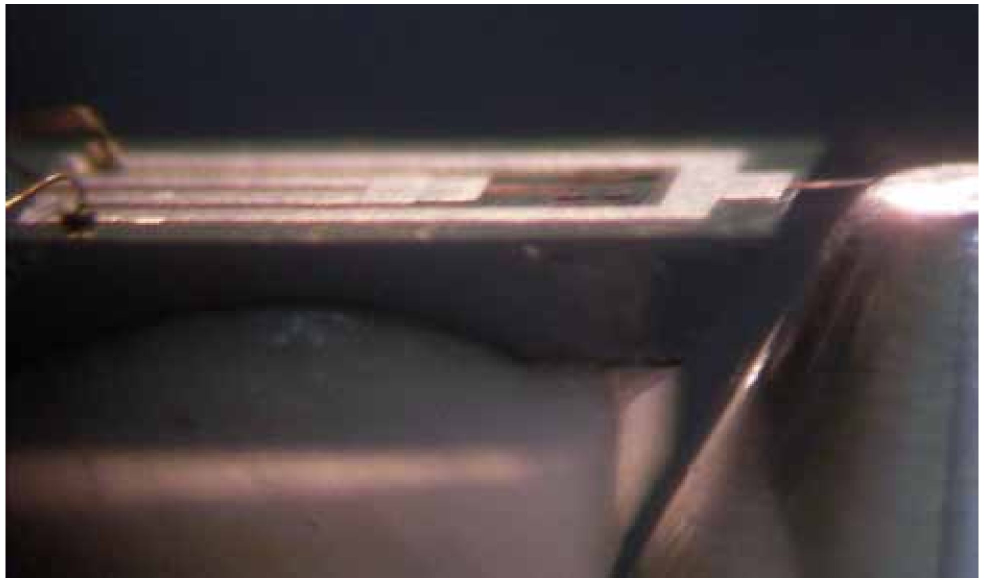


Relative expanded uncertainties with 95% confidence level:
For reduced modulus: **6.8%**
For indentation hardness: **6.3%**

Cantilever Stiffness Measurement



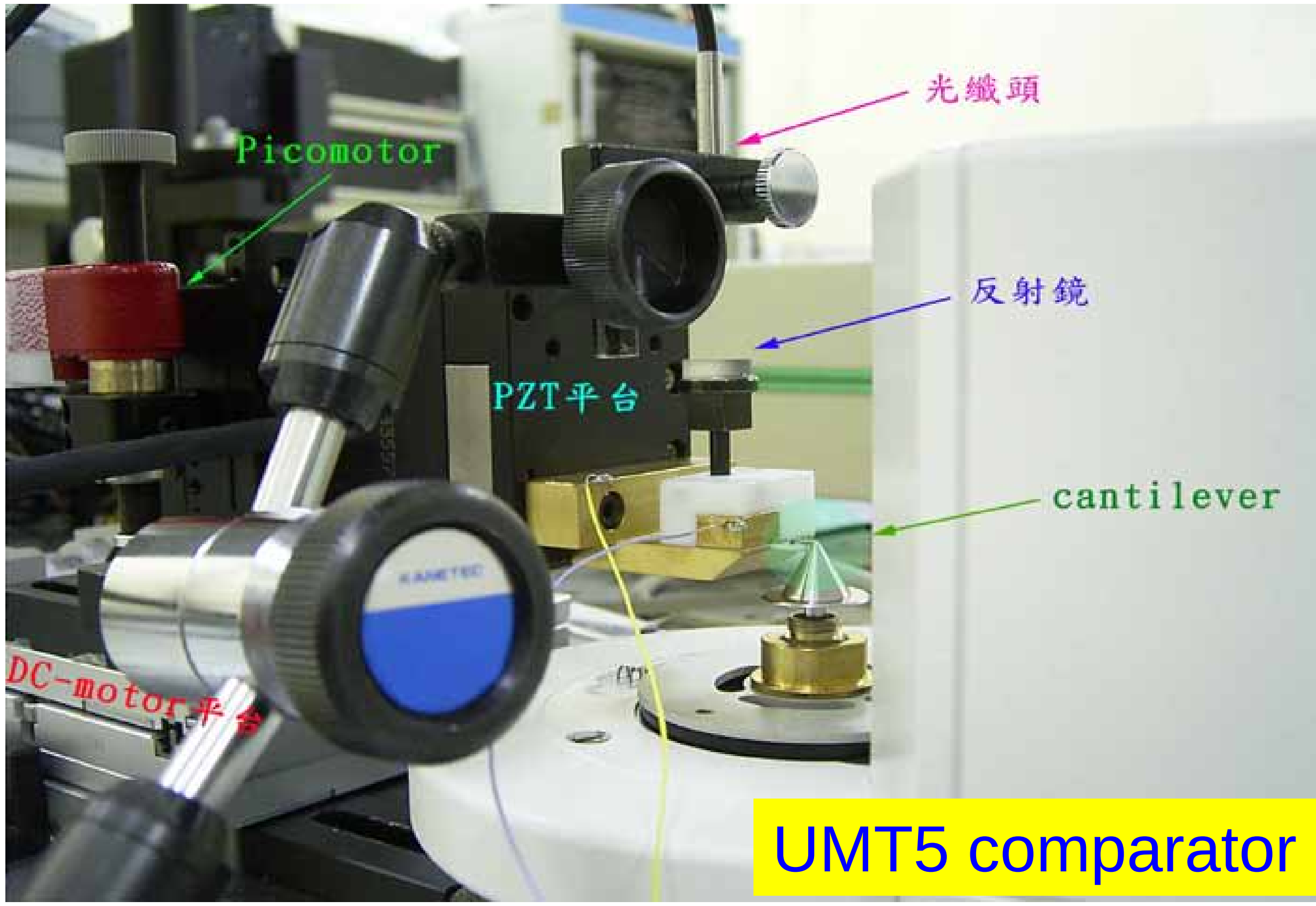




Force: below 50 mN

Stiffness: 0.5 N/m ~ 10 N/m

Uncertainty: 20%(k=2)



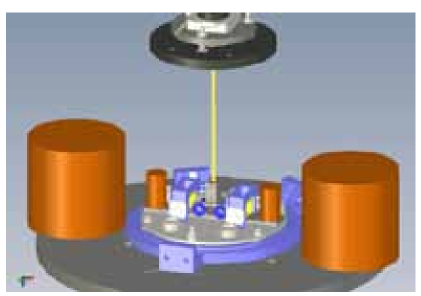
3.Small force measurement schemes in CMS

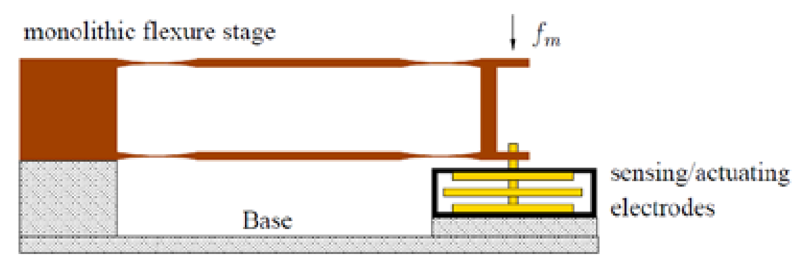
SI unit	kg, m, watt, reflectivity, volt, farad

1 pN — 10 nN — 100 nN — 10μN

Realization of Force Standard

- Light actuation **F = P(1+r)/c**
- Universal gravitation ***F* = GMm/*r*²**
- Electrostatic actuation **F = ½V²dC/dx**





Apparatus: Torsion pendulum | Flexure stage with electrostatic force compensation

Horizontal force

Vertical force

Force/probe under calibration

Force measurement

$F = -k\,xx$

Spring constant (N/m) | Deflection (m)

Strip torsion pendulum

Flexure spring

Simple pendulum

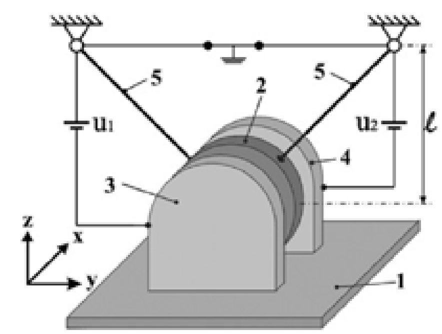
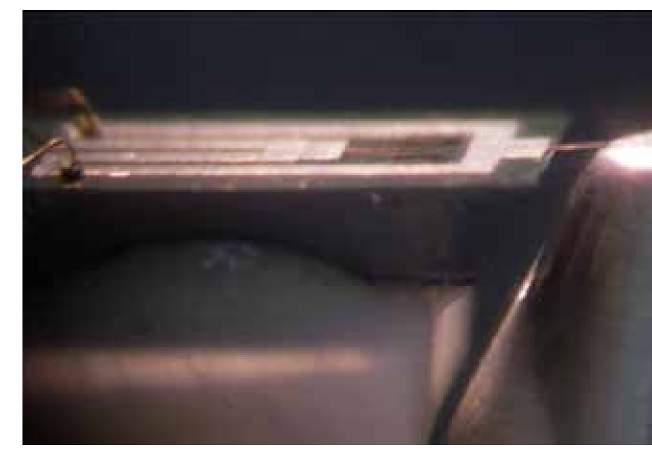


Figure 1. Electrostatic system for stiffness reduction—1: base plate; 2: conductive disc-pendulum; 3, 4: external conductive plates; 5: suspension by a thin conductive wire) ($\ell \approx 0.3$ m).

V. Nesterov, Metrologia **46** (2009) 277-282

AFM cantilever

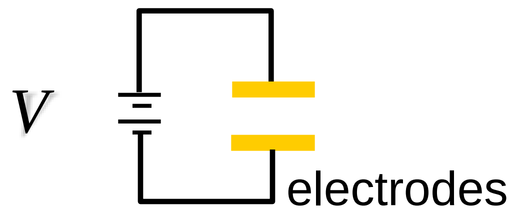


Potential Resolution $\delta F = k \cdot \delta x$

ex: 0.001 N/m ·1 nm = 1 pN

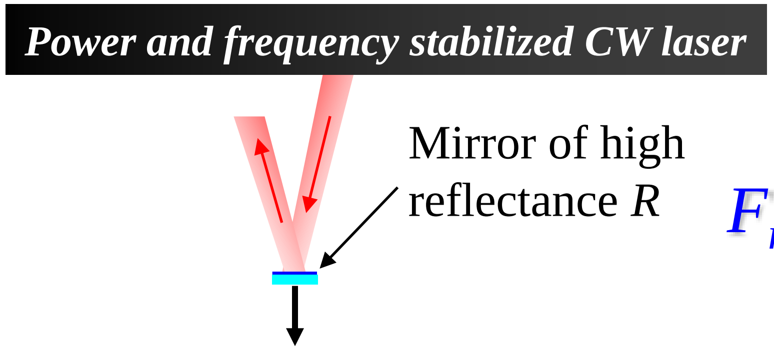
Force balance measurement

- Traceable microforce generation
  - Electrostatic effect
    - Traceable to voltage standard provided traceable capacitance gradient measurement



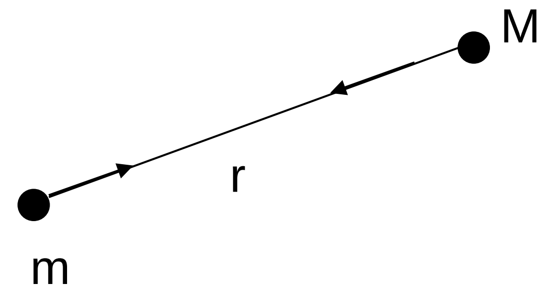
$F_e = \frac{1}{2} V^2\, dC/dx$

  - Radiation pressure
    - Laser with stable power and frequency, plus a mirror



$F_r = P_r(1+R)/c$

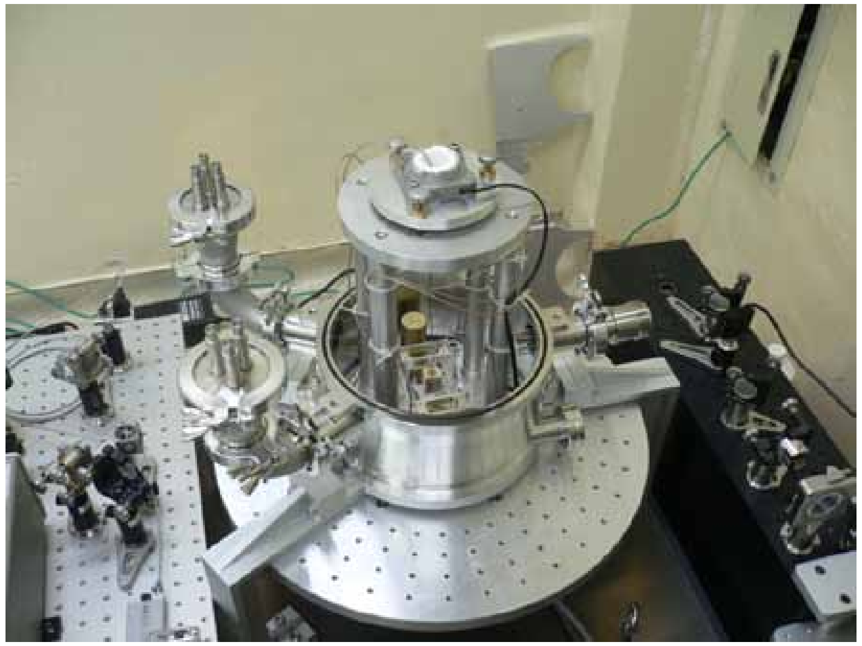
  - Universal gravitation
    - One fundemental constant involved ~ gravitational constant G
    - Masses of kg scale produce force at nanonewton level
    - ***Weakest in all the fundamental forces, and difficult***

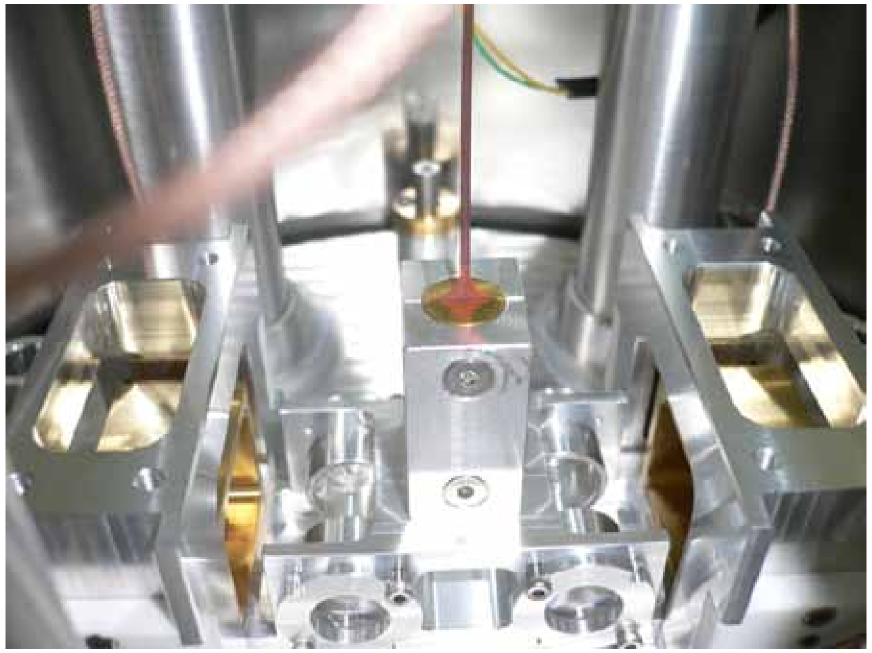


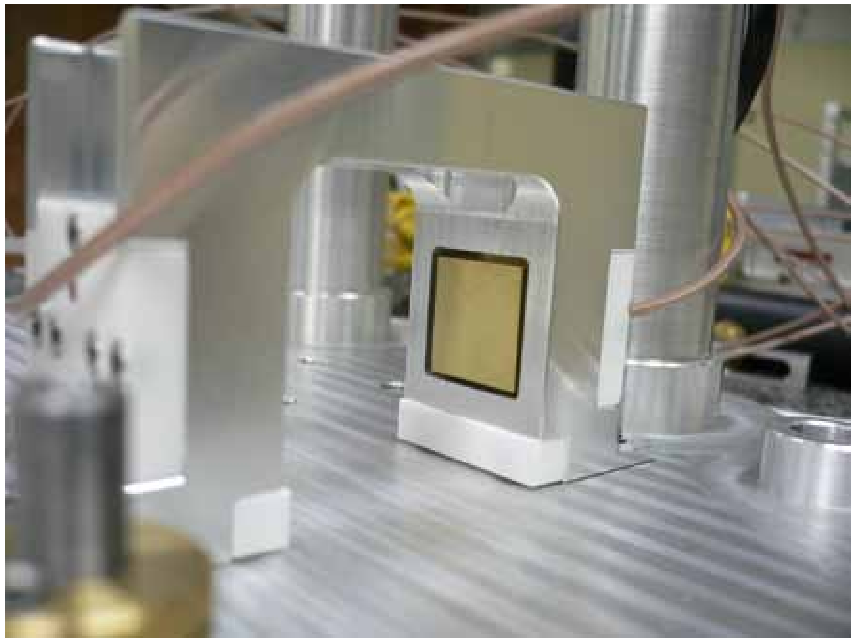
$F_g = GMm/r^2$

3-1.Torsion pendulum facility

- Force range: horizontal force below 50 nN
- Target resolution: few piconewton
- Mechanical spring: strip torsion pendulum
- Compensation force: ***radiation pressure force***, ***electrostatic force*** and ***universal gravitation***

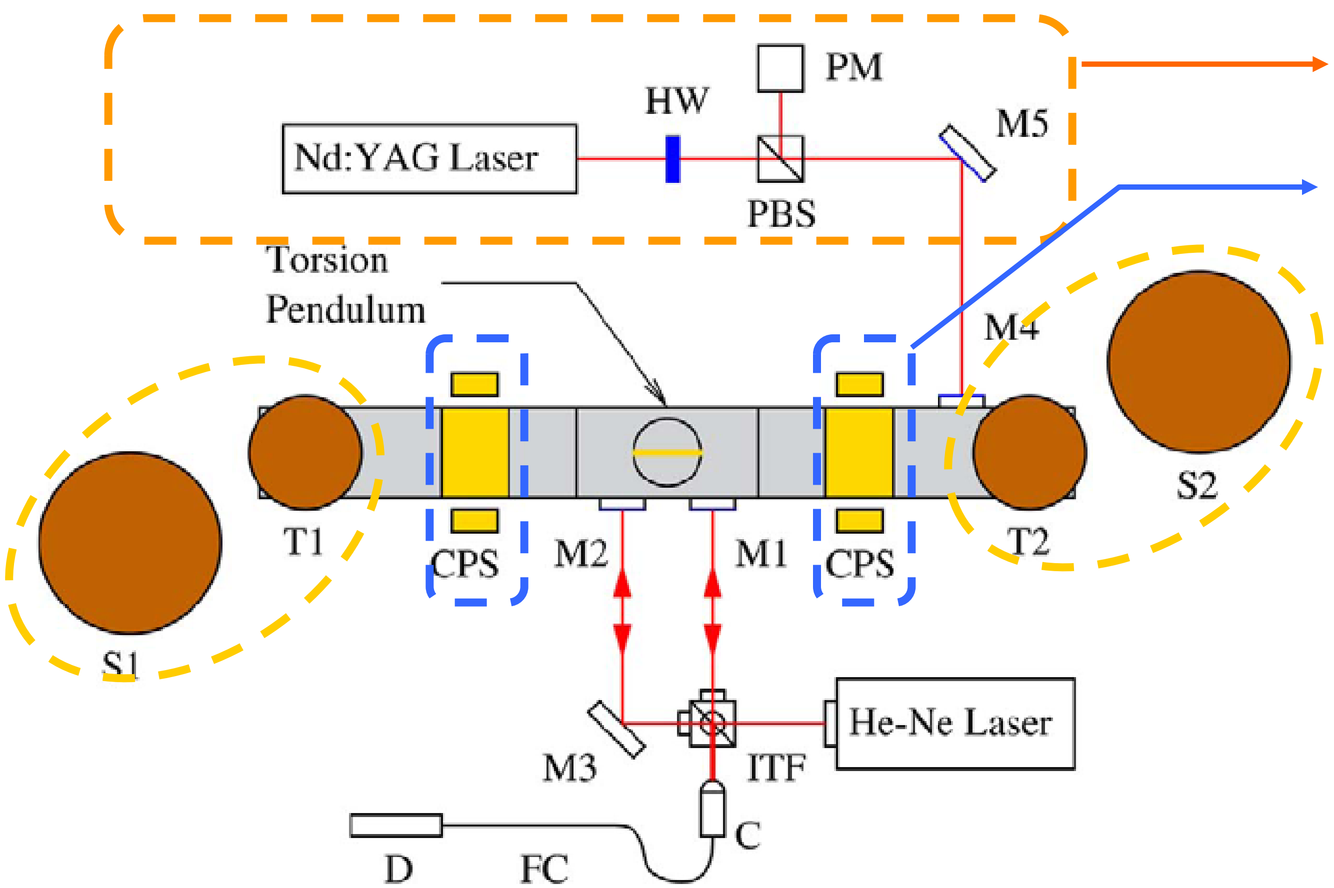






Torsion pendulum facility

Top view:

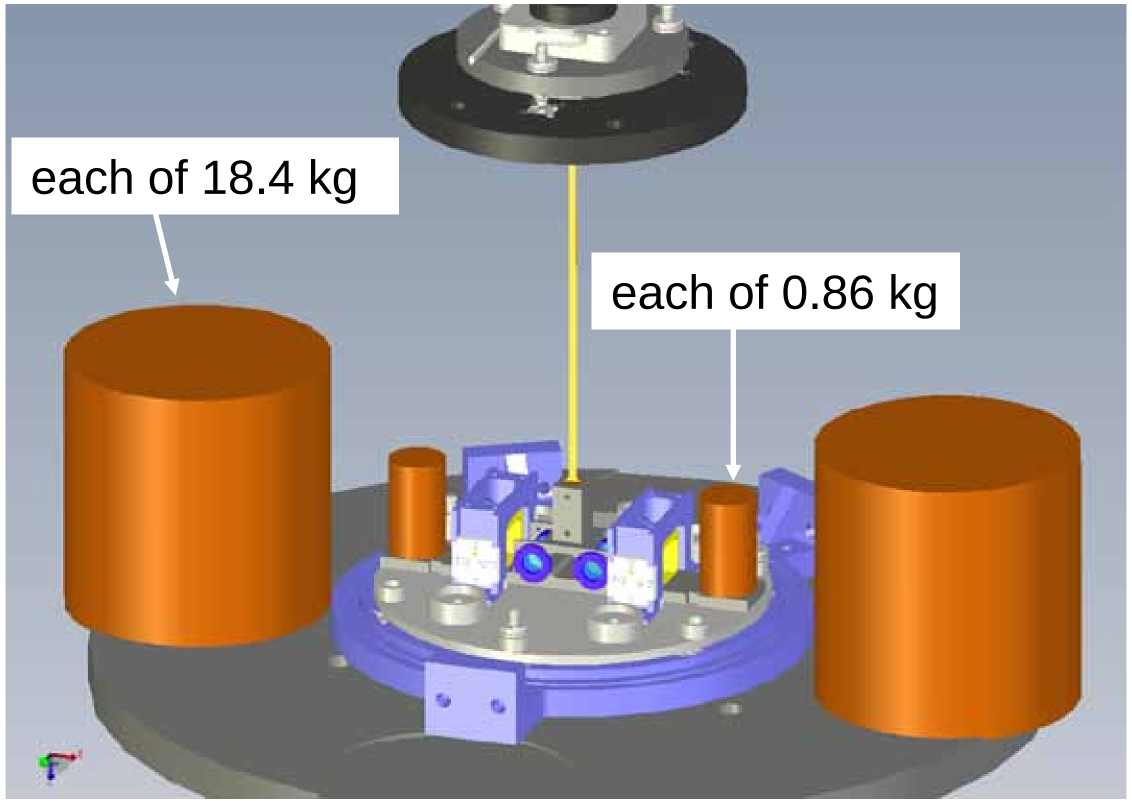


Radiation pressure force

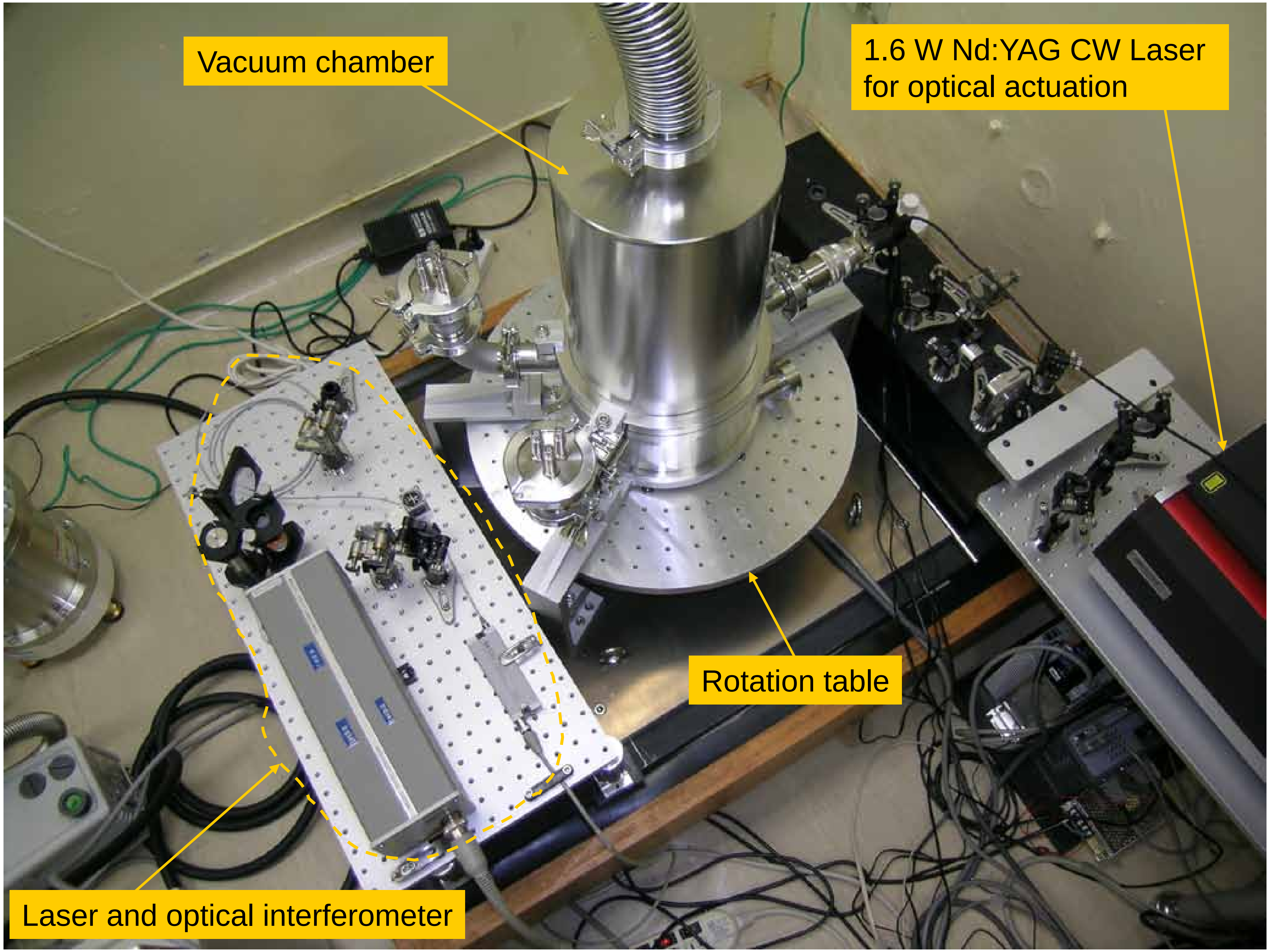
Electrostatic force

Universal gravitation

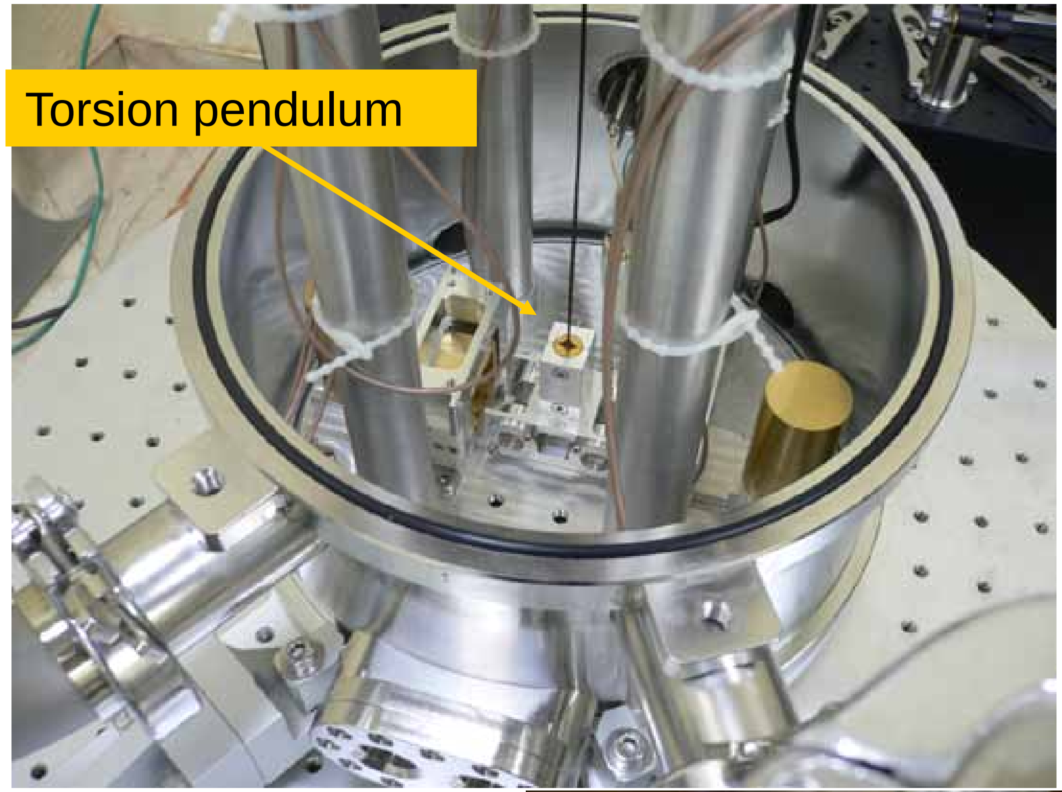
Schematic view of experimental setup. T1 and T2: Test masses. S1 and S2: Source masses. ITF: Interferometer. CPS: Capacitive position sensor. M1 to M5: Reflection mirrors. C: Collimator. FC: Fiber cable. D: Photodetector. PBS: Polarizing beam splitter. PM: Power meter.

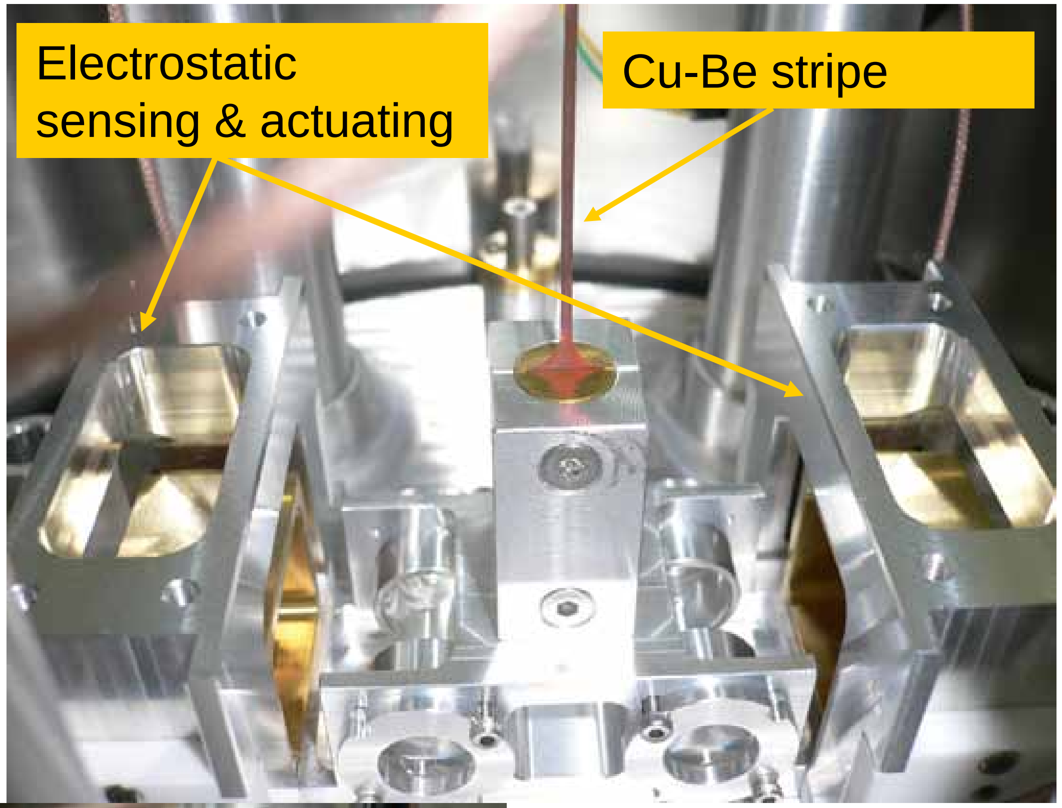


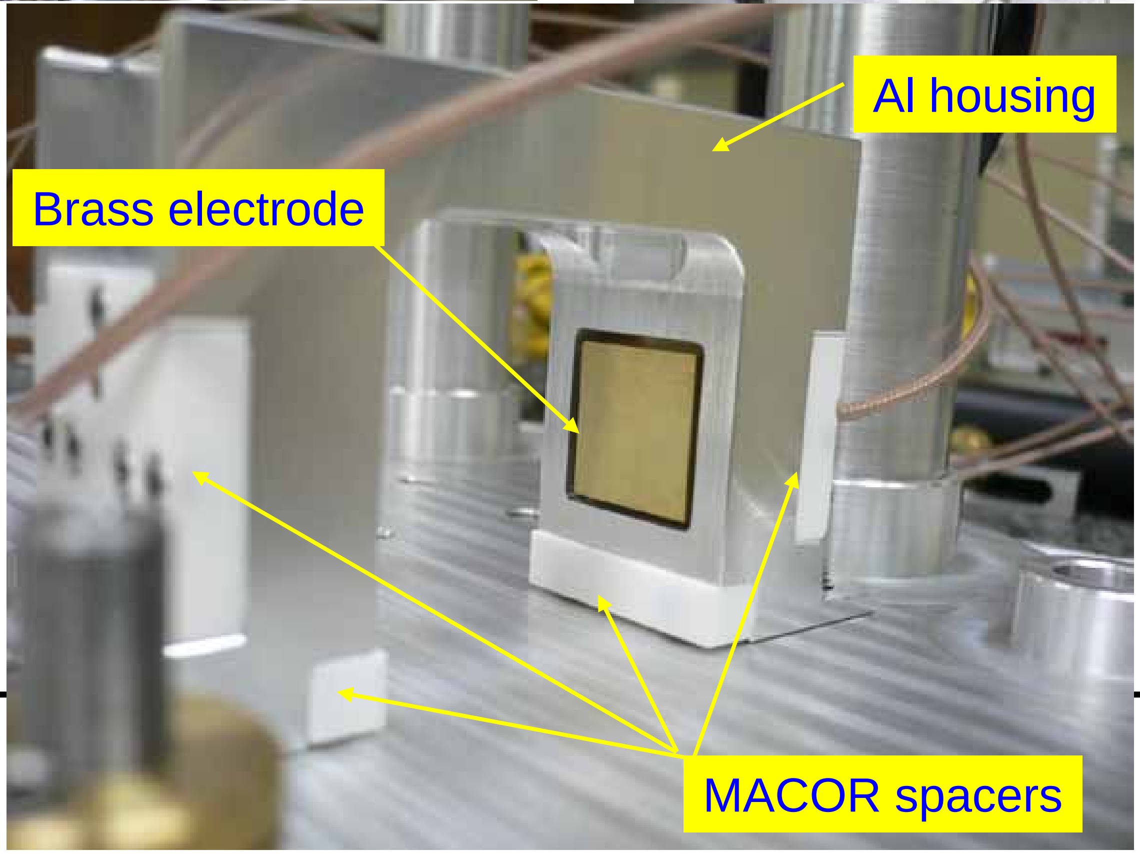
Torsion pendulum experiment



Torsion pendulum experiment







Strip torsion pendulum

Cu-Be strip

Thickness *t*: 27 mm

Width *b*: 1.2 mm

Length *L*: 200 mm

Spring constant is dominated by the **load**, not the **material's properties**

$$k_t = Mgb^2 / 12L + bt^3F / 3L$$

T.J. Quinn *et al*, *Metrologia*, 1997, **34**, 245-249

=> Reducing influence of noises resulting from thermal fluctuations and anelasticity

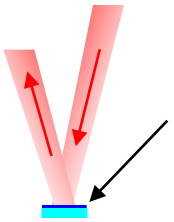
$$k(1+if(w))$$

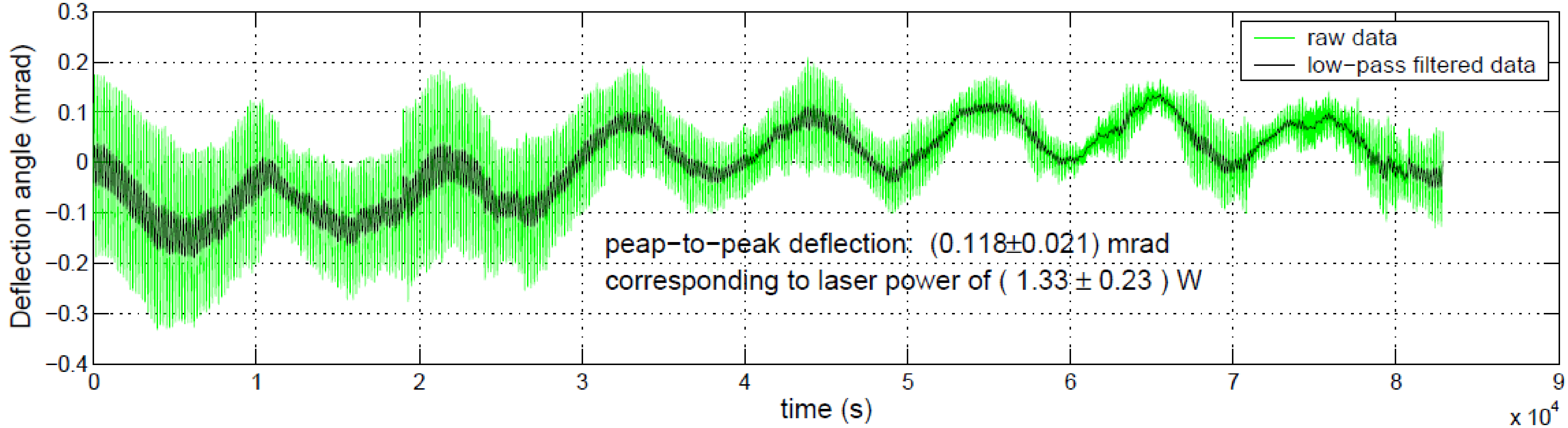
Torsional spring constant:
k_t = 5.25 ´ 10^{-6} Nm/rad

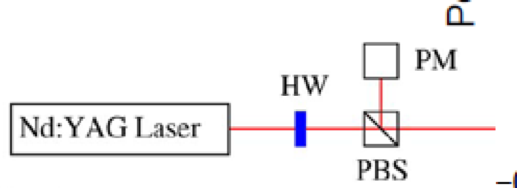
Or $k_{linear} = k_t / l^2$ = 0.001 N/m
(for *l* = 70 mm)

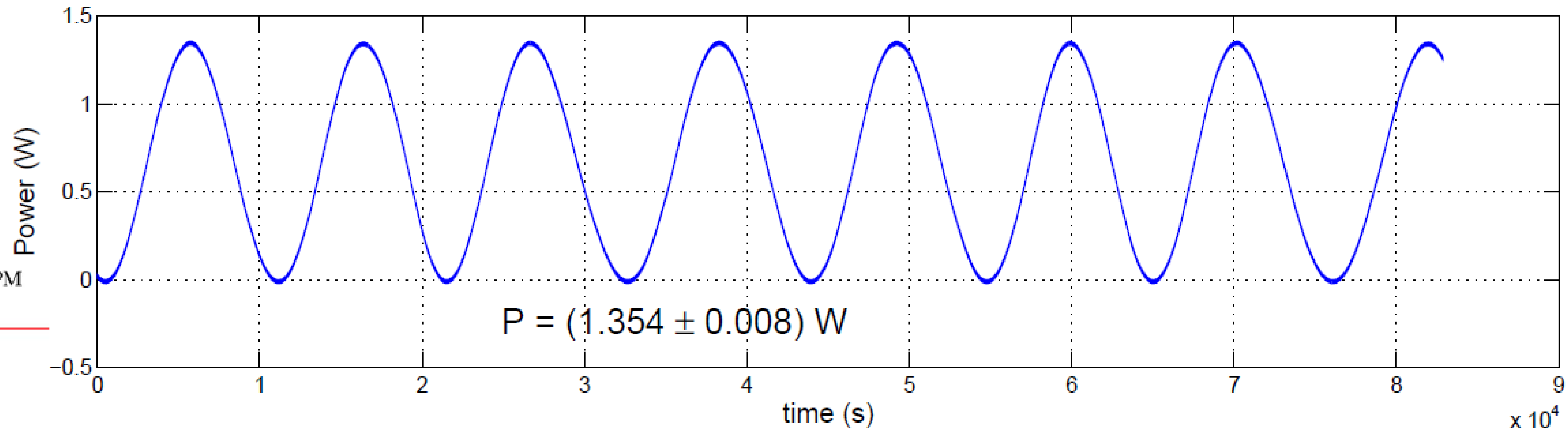
F: shear modulus

Radiation pressure force









Damp the resonant motion without increasing the thermal noise µ $\sqrt{4k_B Tb}$
=> active damping

Active damping control using light pressure force

$$I\ddot{\theta} + b\dot{\theta} + k\theta = \tau_a + \tau_n \qquad \tau_a = -K\dot{\theta}$$

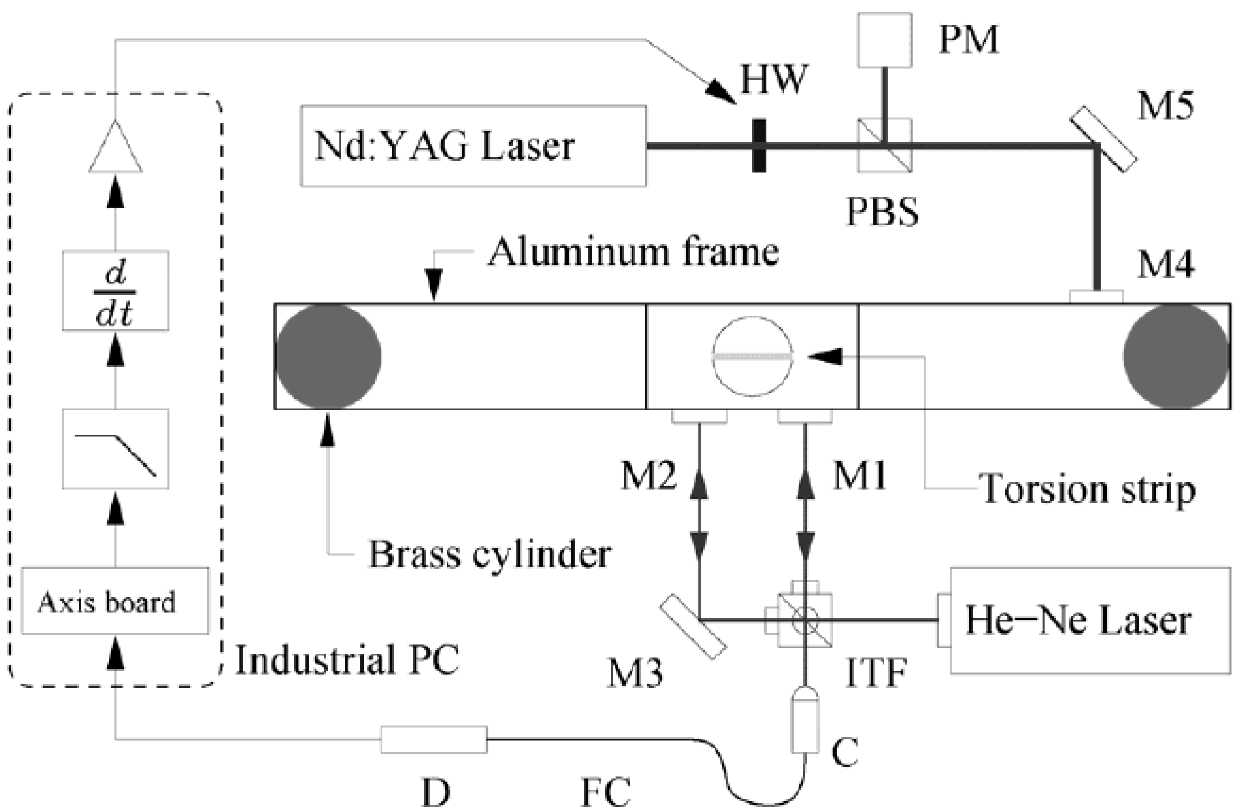


FIG. 1: Schematic view of experimental setup. ITF: interferometer; M1 to M5: reflection mirrors; C: collimator; FC: Fiber cable; D: photo-detector; PBS: polarizing beam splitter; PM: power meter.

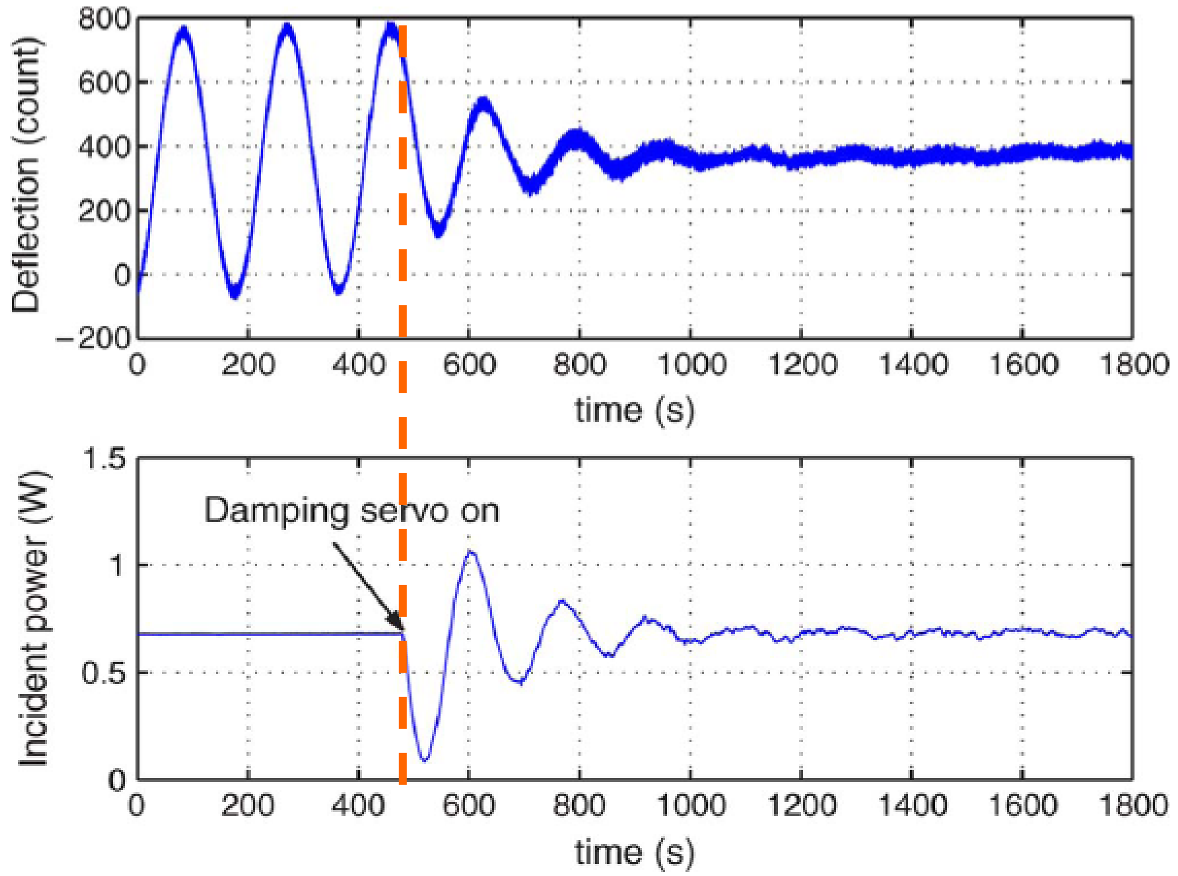
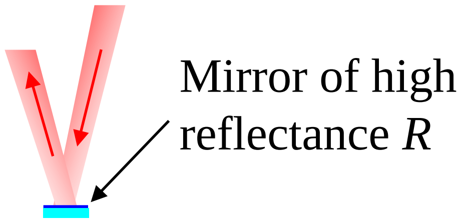


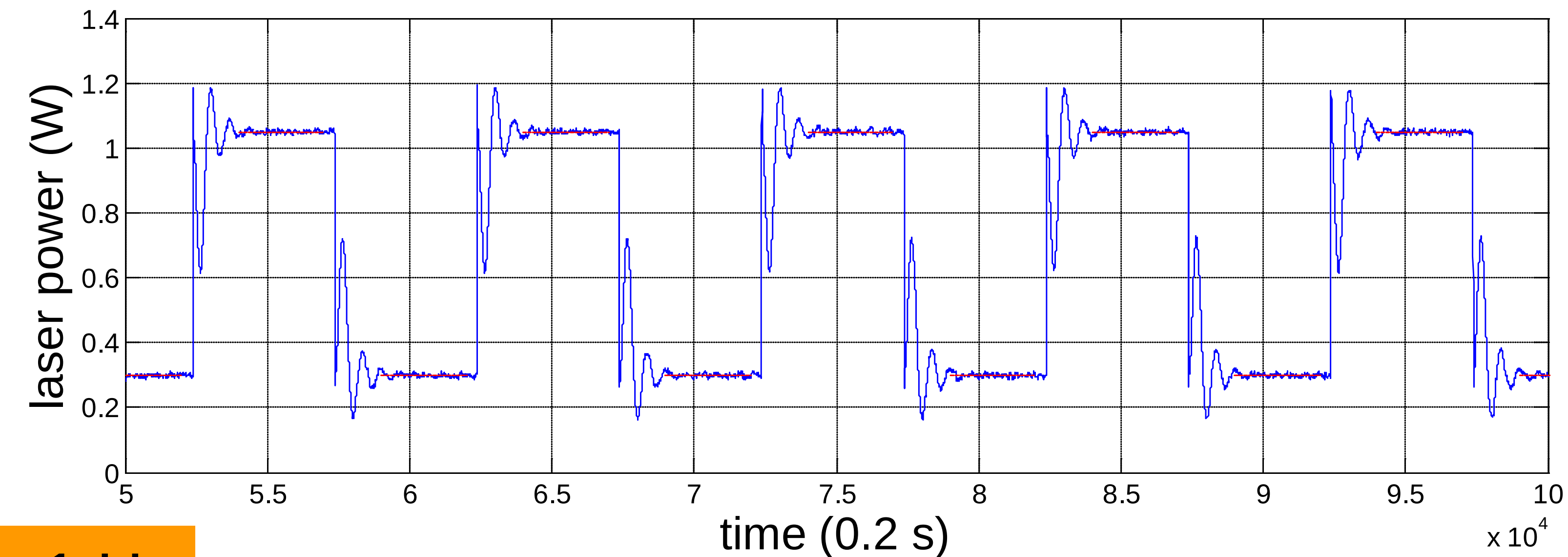
Fig. 5. Damping created by the radiation pressure force. (Top) Deflection measured by the interferometer (one count corresponds to 10 nm). (Bottom) Incident power on the mirror M4. After the damping servo was switched on, the incident power was varied to generate the torque needed to damp the pendulum's motion.

Radiation pressure force

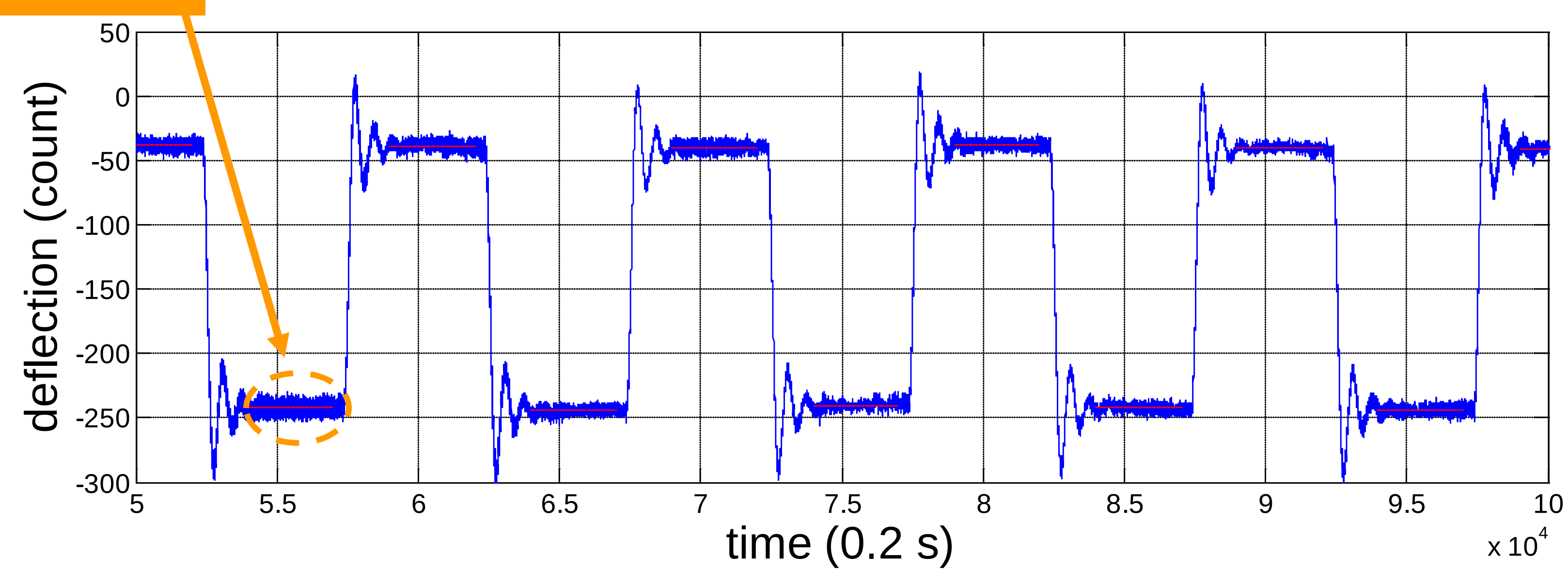


P=0.75 W

2P/c=5.0 nN



Small pendulum motion at ~ 1 Hz

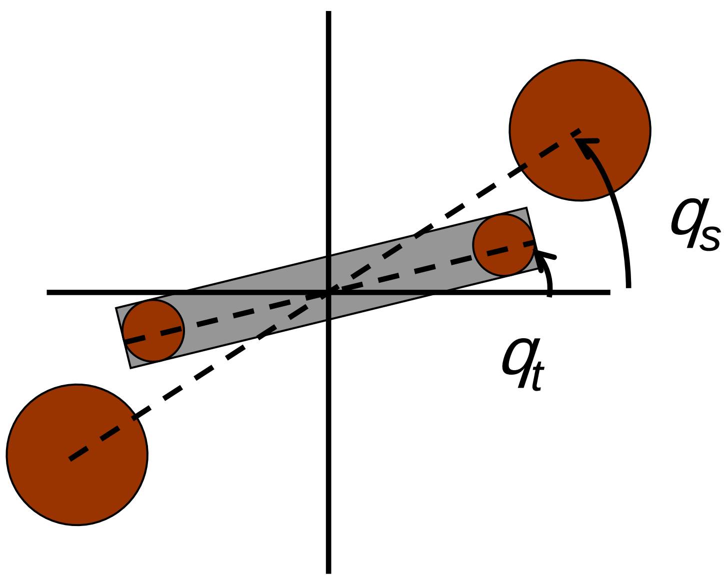


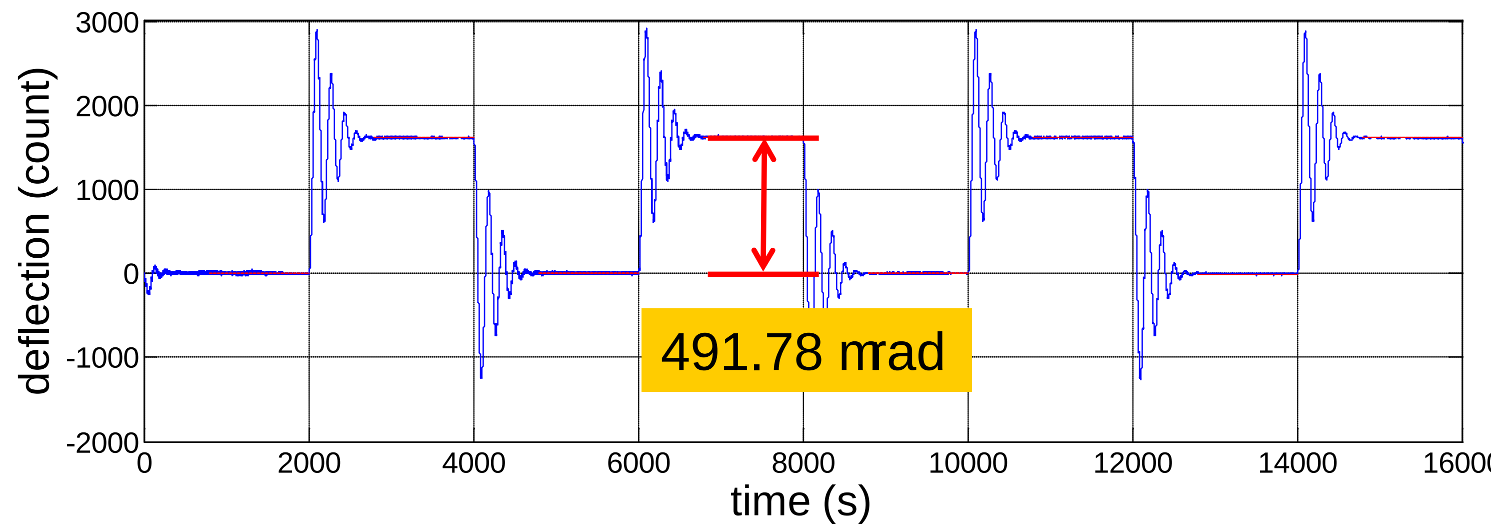
Measurement:
4.9 ± 0.4 nN

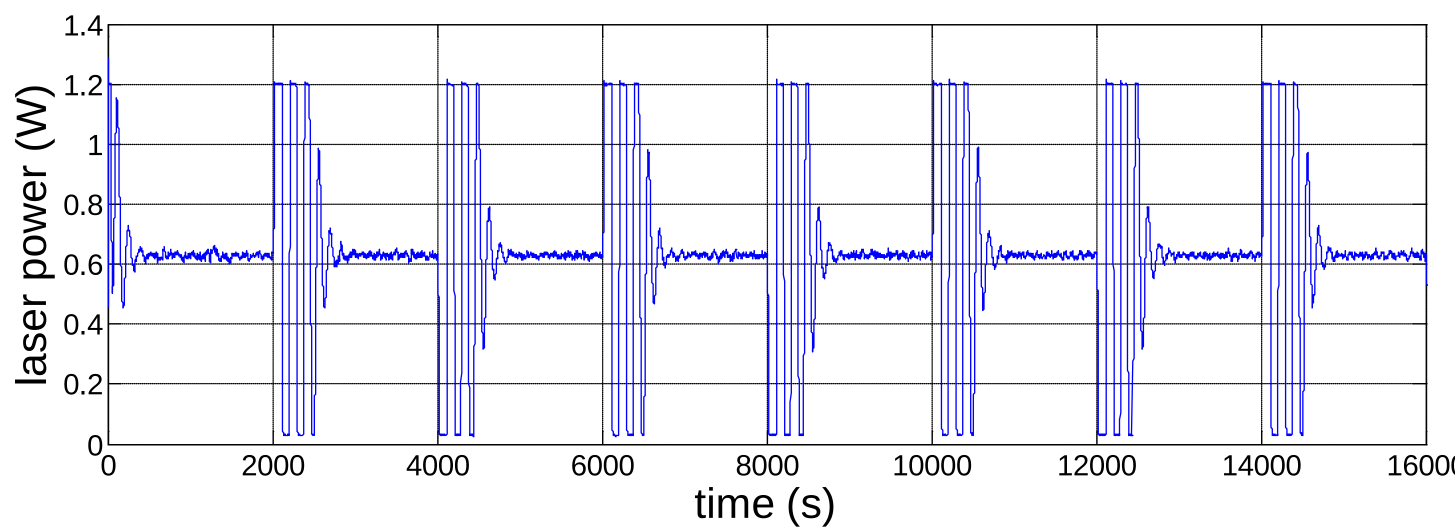
S-J Chen and S-S Pan, *"Nanonewton force generation and detection based on a sensitive torsion pendulum"*, IEEE Trans. Instru. Meas. **58** (2009) 897-901

Optical pressure Calibration by Universal Gravitation

To have the torsion pendulum quickly reach its equilibrium position, radiation pressure force was used to damp the resonant motion.





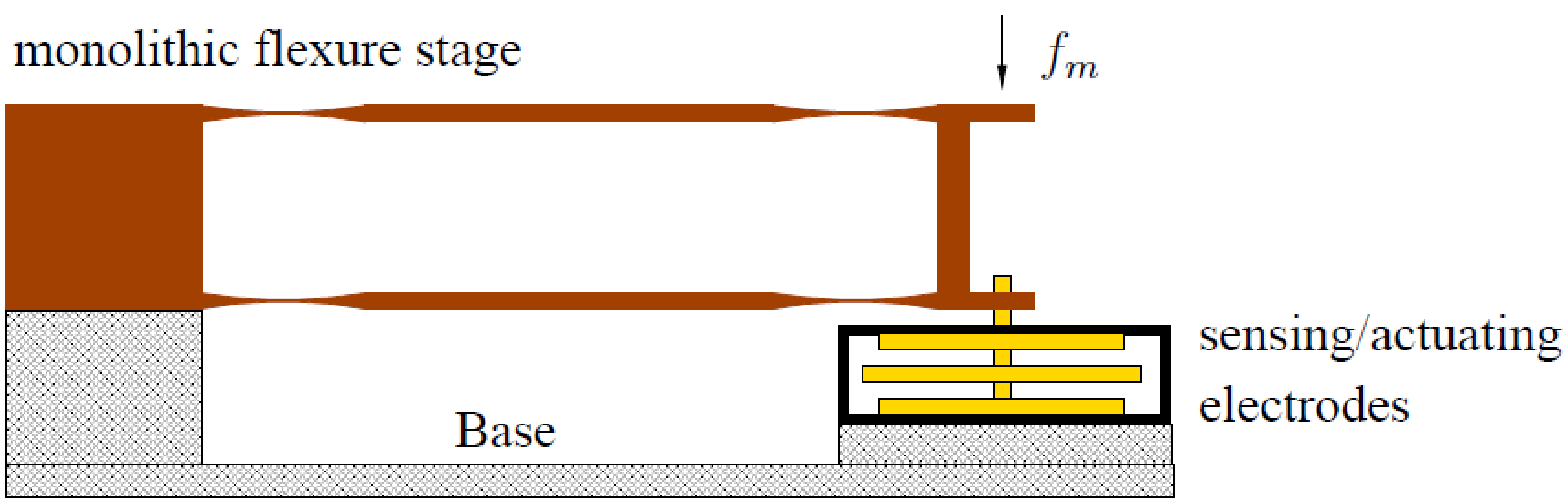


$F_g = GMm/r^2$

Work is in progress…..

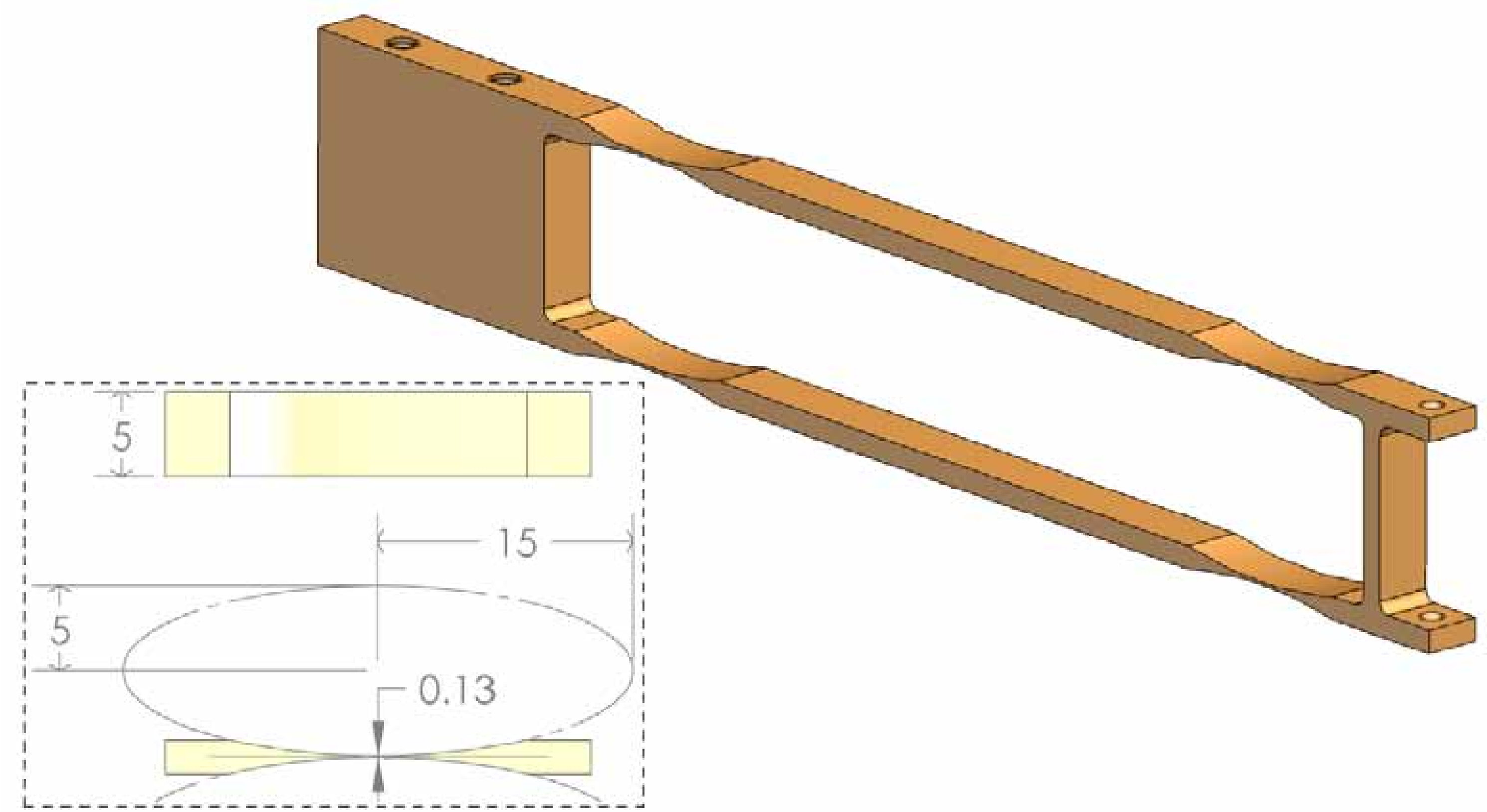
3-2.Flexure stage with electrostatic sensing and actuating

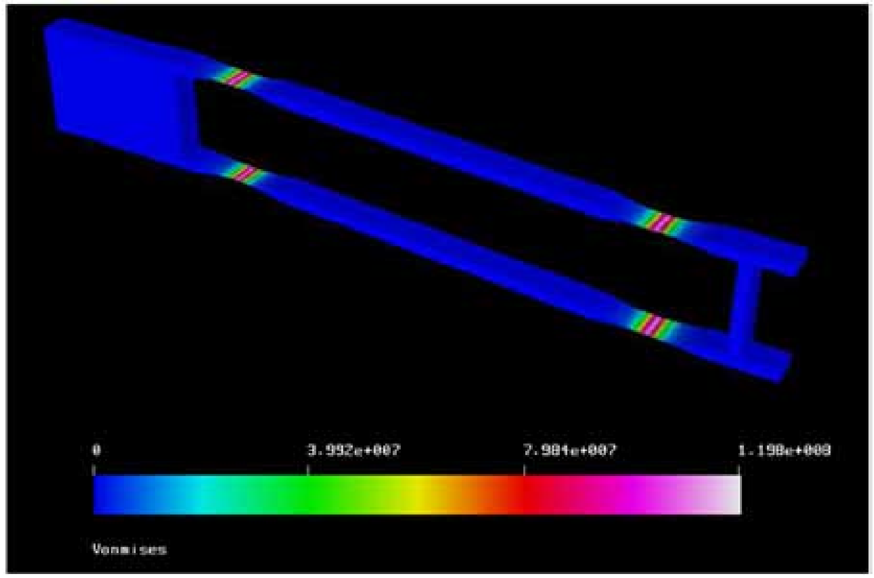
- Force range: vertical force below 200 mN
- Target resolution: few nanonewton
- Mechanical structure: monolithic flexure stage
- Compensation force: electrostatic force

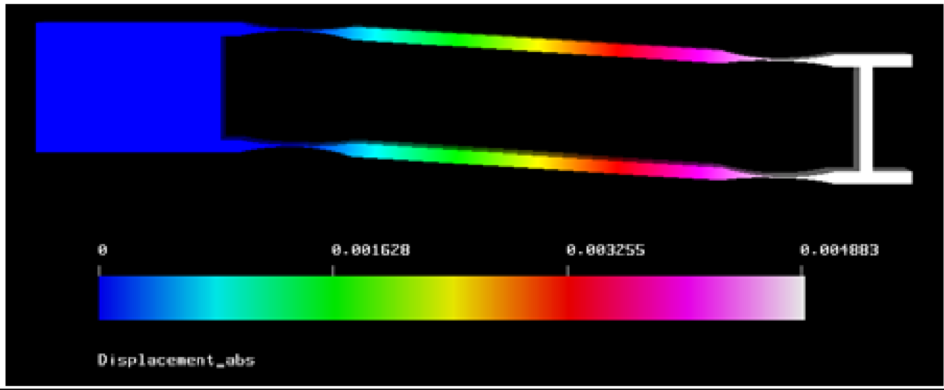


Monolithic flexure structure

- Flexure-pivot: elliptical notch type
- Four pivots for rectilinear motion
- Material: aluminum alloy (Al 6061-T6), copper-beryllium (C-17200)
- Stiffness: 16.32 N/m and 19.1 N/m



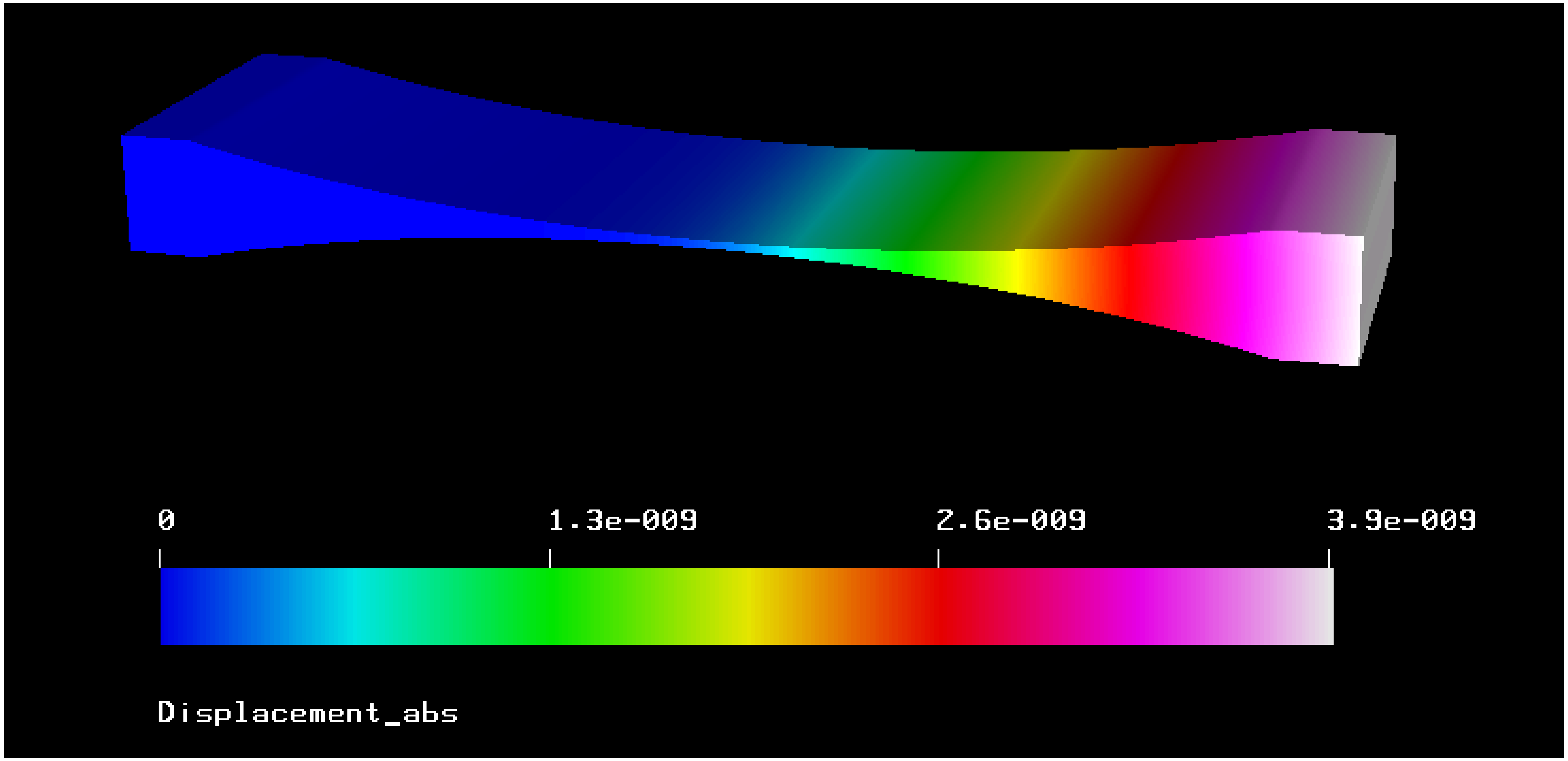




Low stiffness flexures

Low stiffness flexure

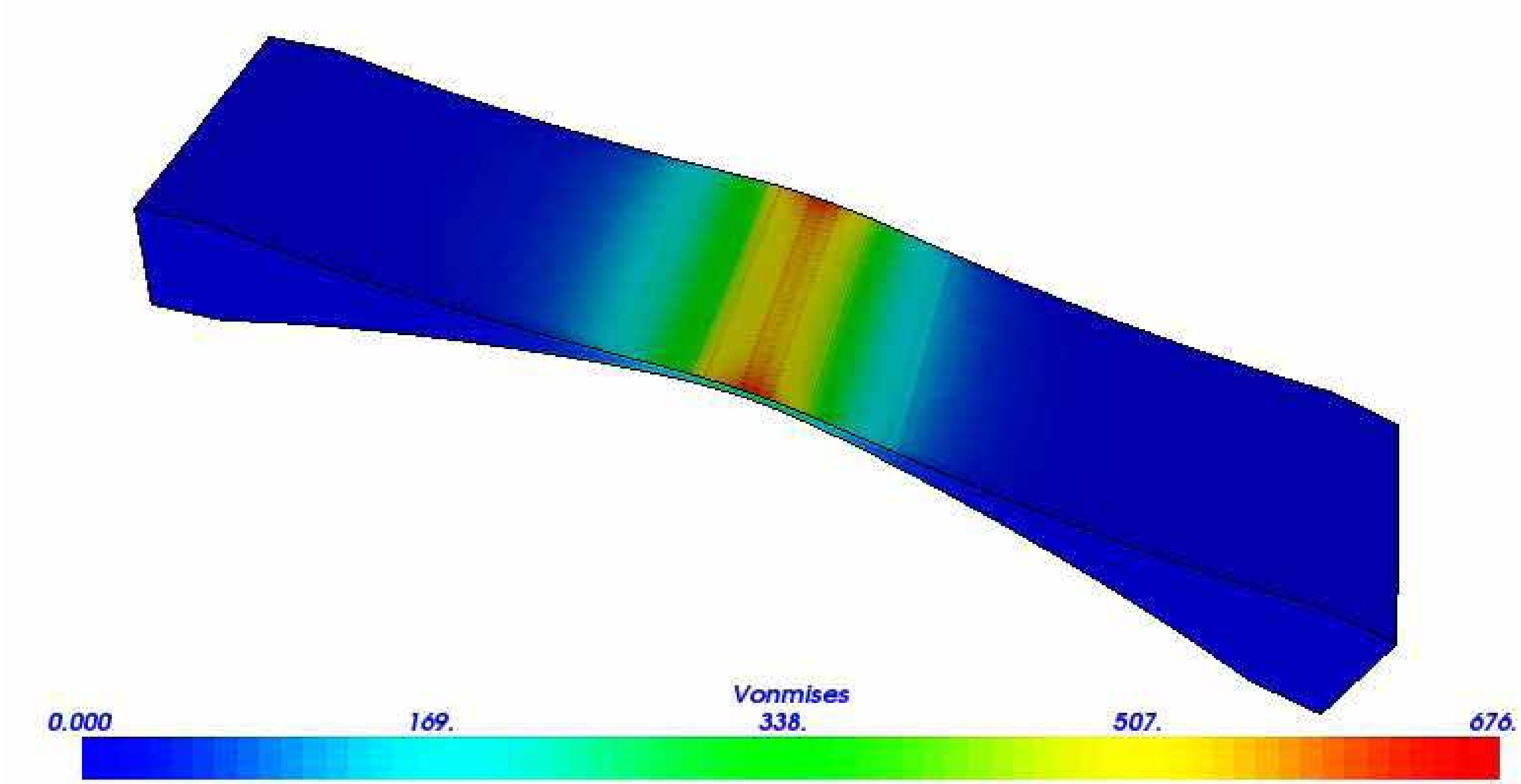
- Finite element analysis



The simulated displacement under a load of 1 mN. The displacement unit is in meter.

Low stiffness flexure

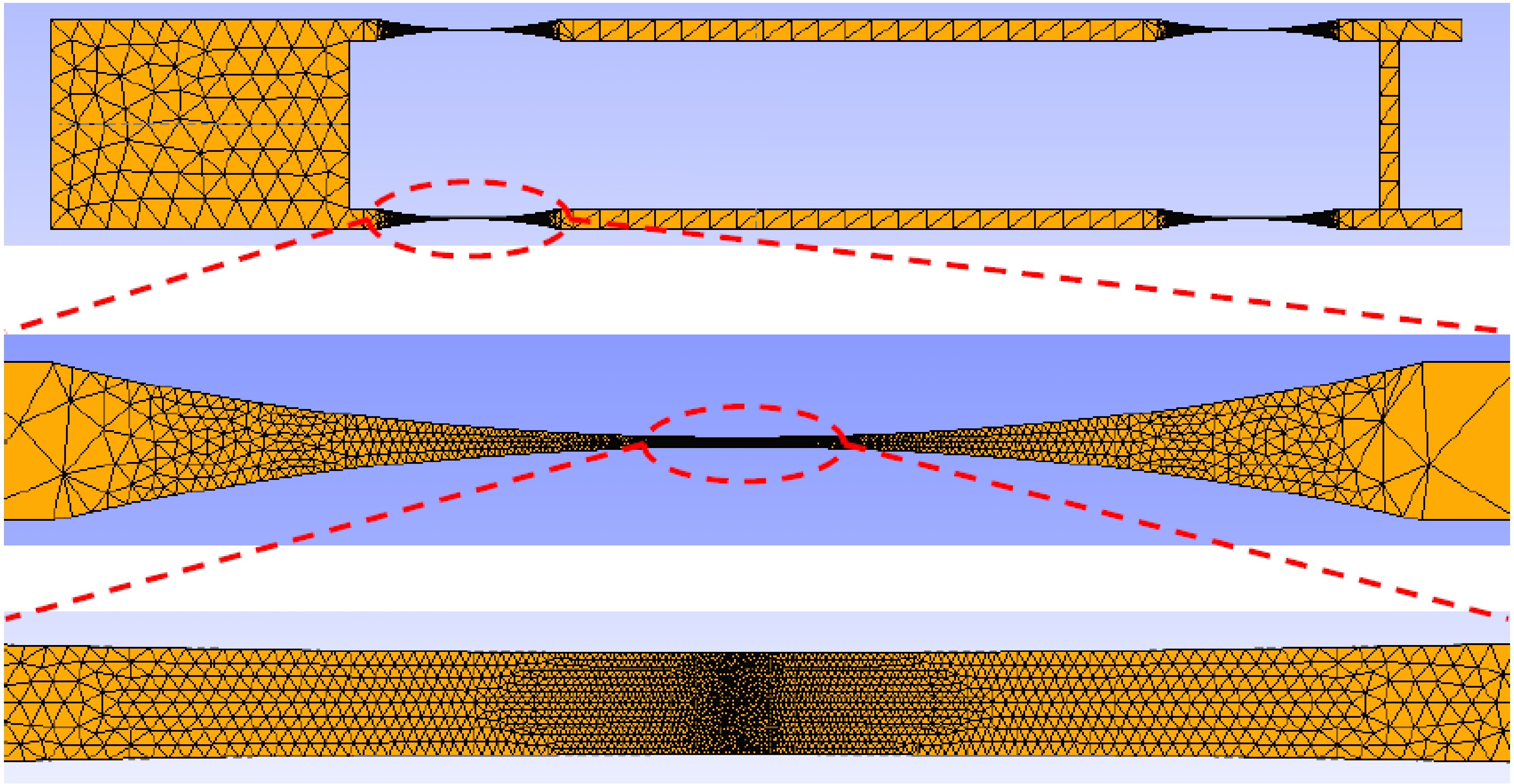
- Finite element analysis



Stress distribution under a load of 1 mN. The maximum stress is localized at the thinnest portion of the hinge. The stress unit is in N/m^2.

Low stiffness flexure

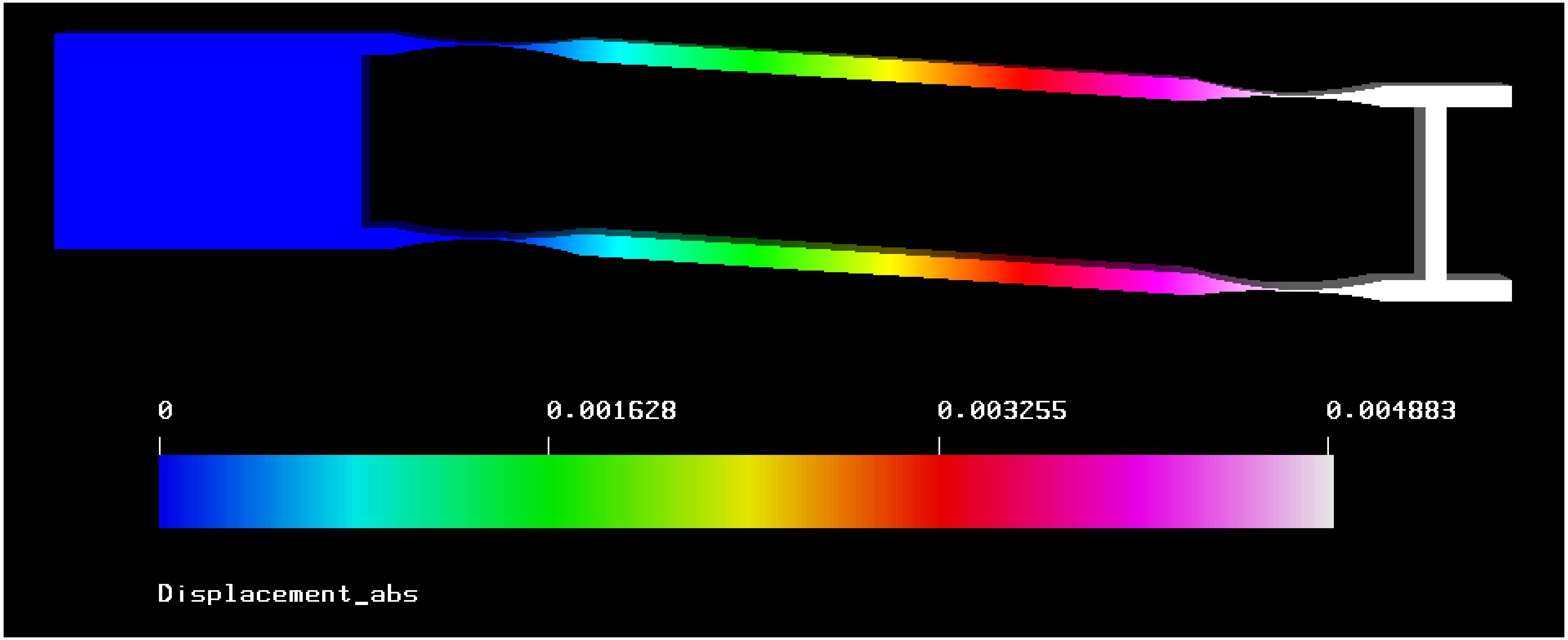
- Finite element analysis



The mesh model of the structure constructed by 20,467 volume elements with a element size ranging from 0.5 mm to 5 mm.

Low stiffness flexure

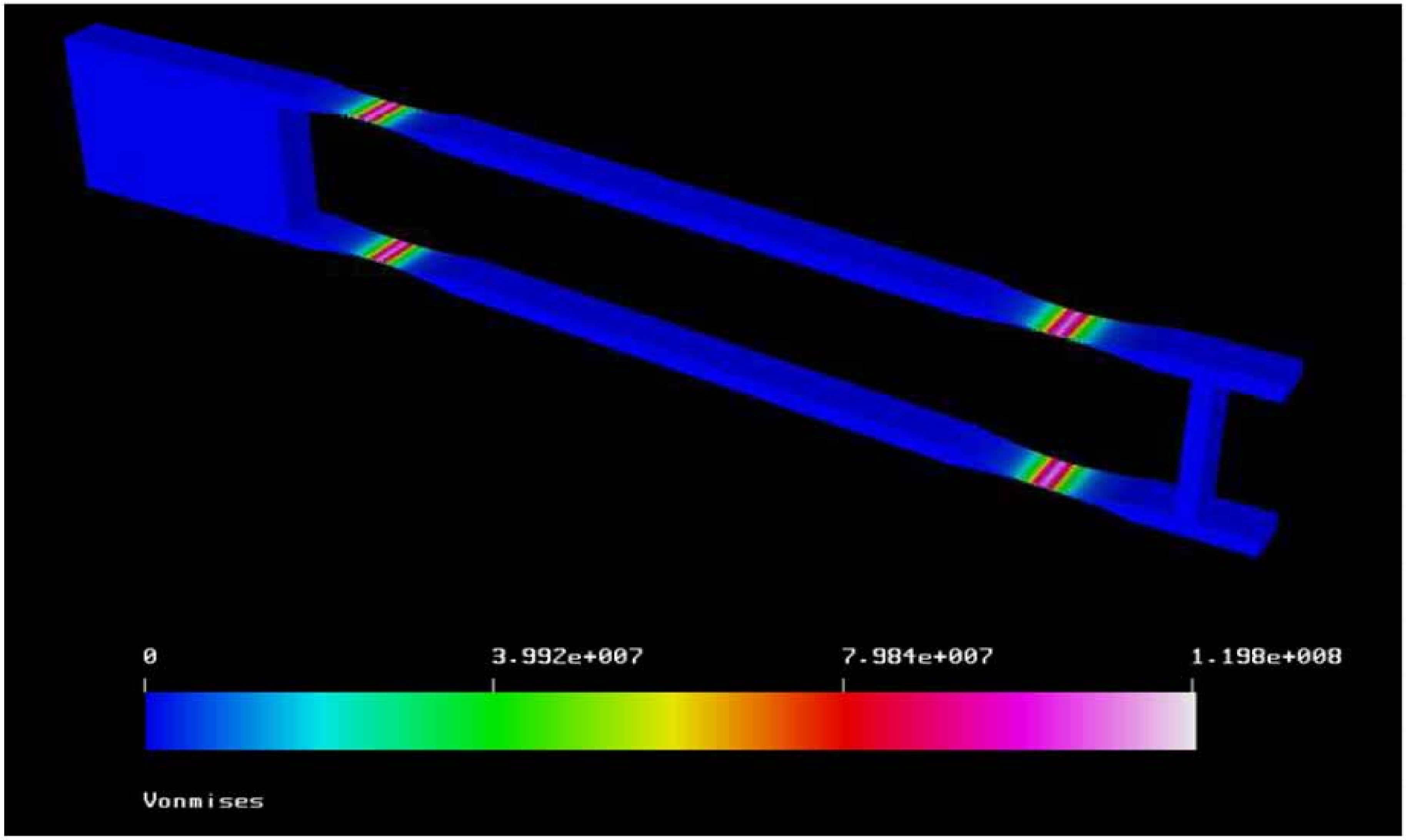
- Finite element analysis



The deflection due to the structure's bodyweight and the load of disk electrode (about 6.93 g).

Low stiffness flexure

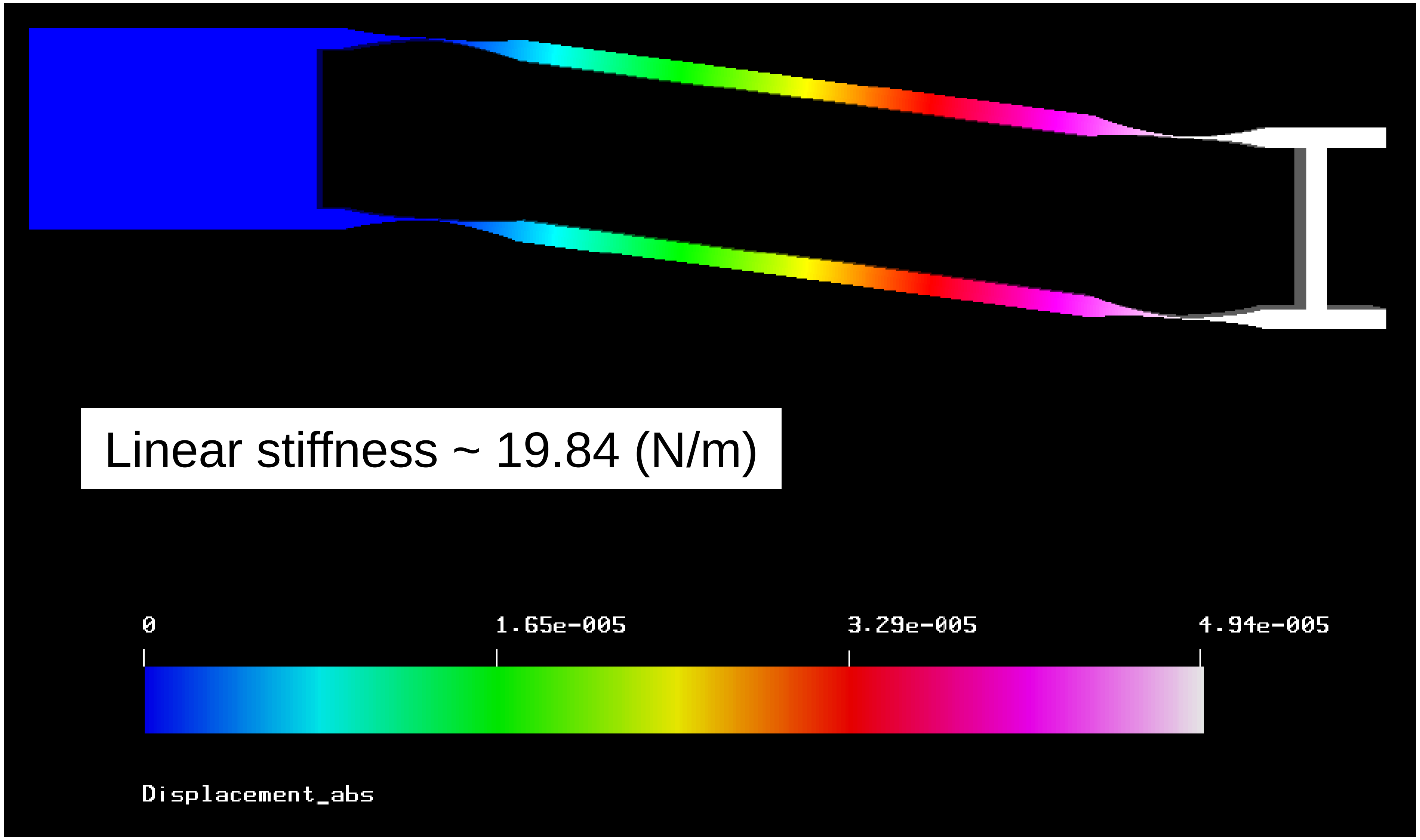
- Finite element analysis



The stress due to the structure's bodyweight and the load of disk electrode.

Low stiffness flexure

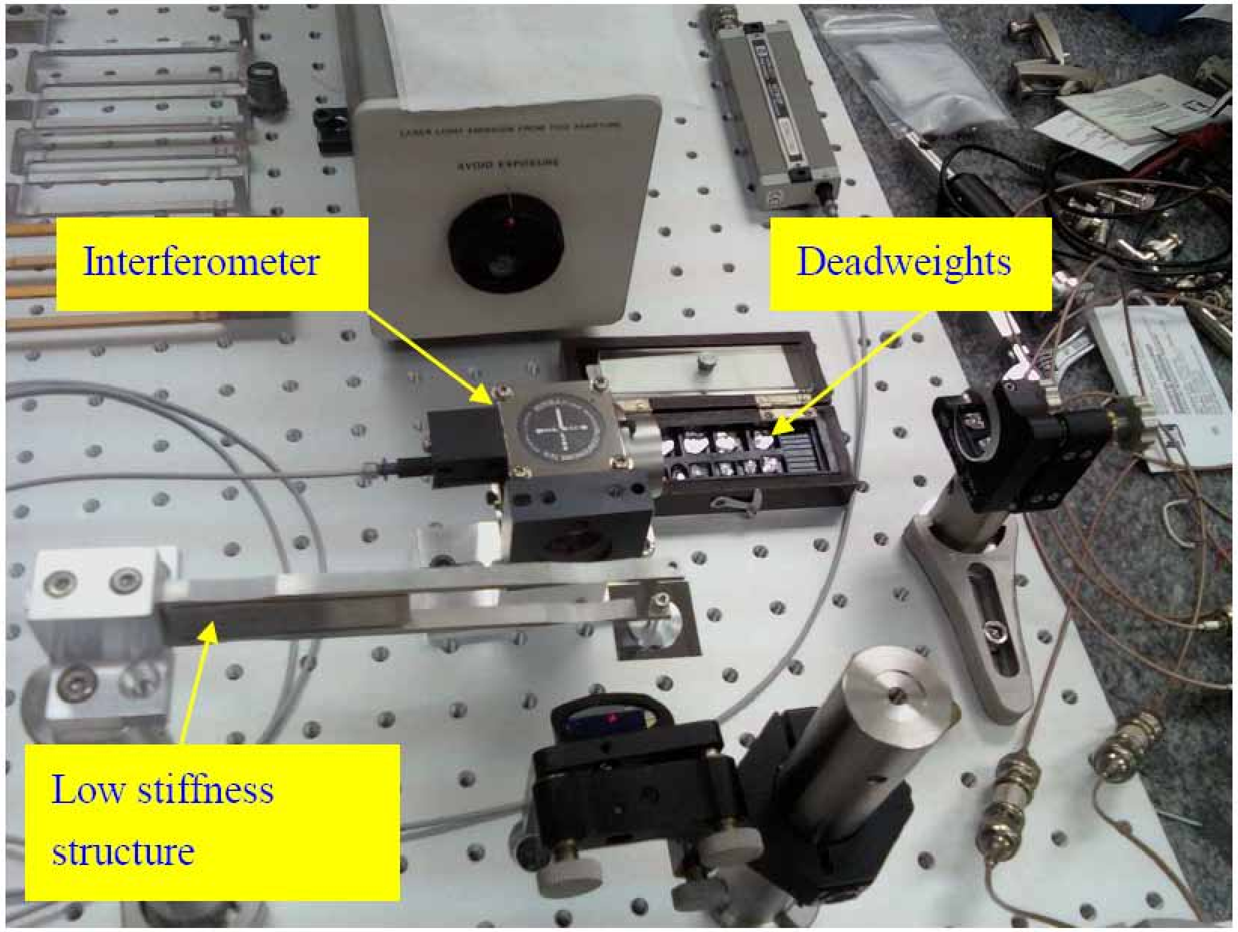
- Finite element analysis

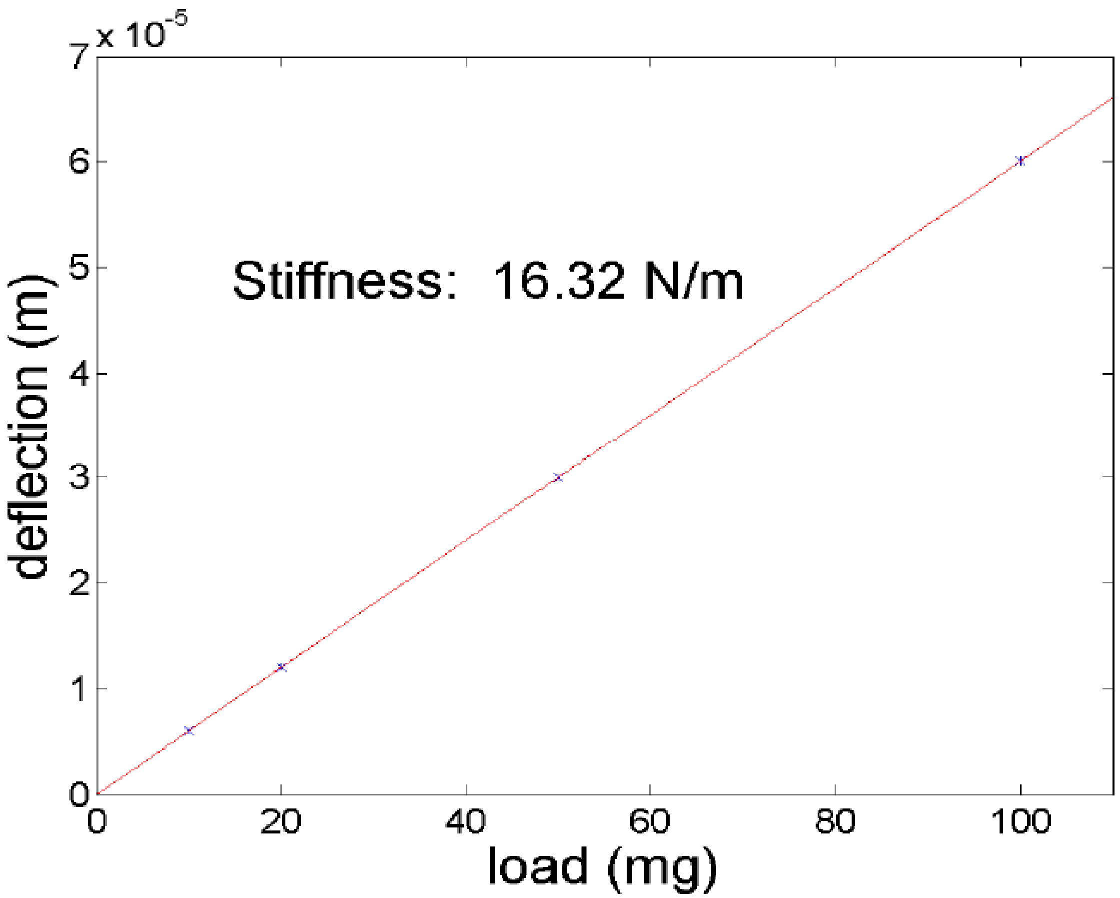


The deflection under a load of 100 mg.

Low stiffness flexure measurement

- Stiffness measurement





Force balance control

Differential capacitance sensing:

$$\Delta C = C_1 - C_2 \approx \frac{2\varepsilon A}{d^2} x$$

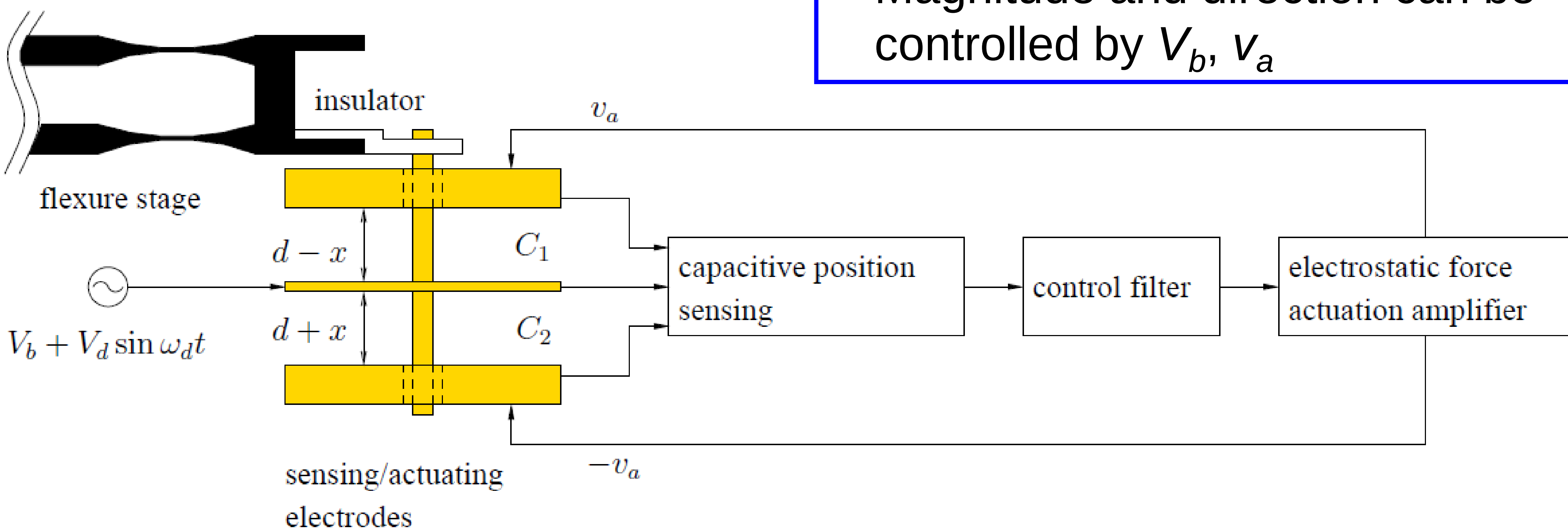
Measured at high frequency (100 kHz)

Electrostatic force actuation:

$$f_e = \frac{1}{2}\frac{dC_1}{dx}(V_b + v_a)^2 - \frac{1}{2}\frac{dC_2}{dx}(V_b - v_a)^2$$

$$= 2\left.\frac{dC_1}{dx}\right|_{x=0} V_b v_a$$

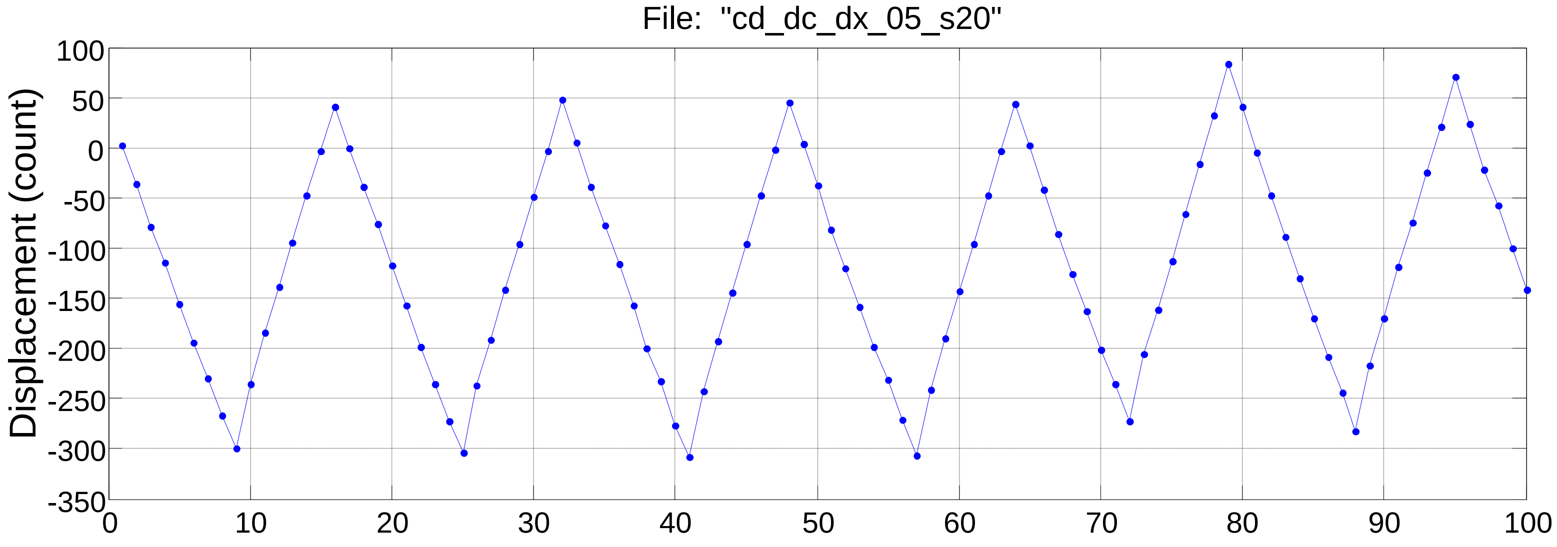
Magnitude and direction can be controlled by V_b, v_a



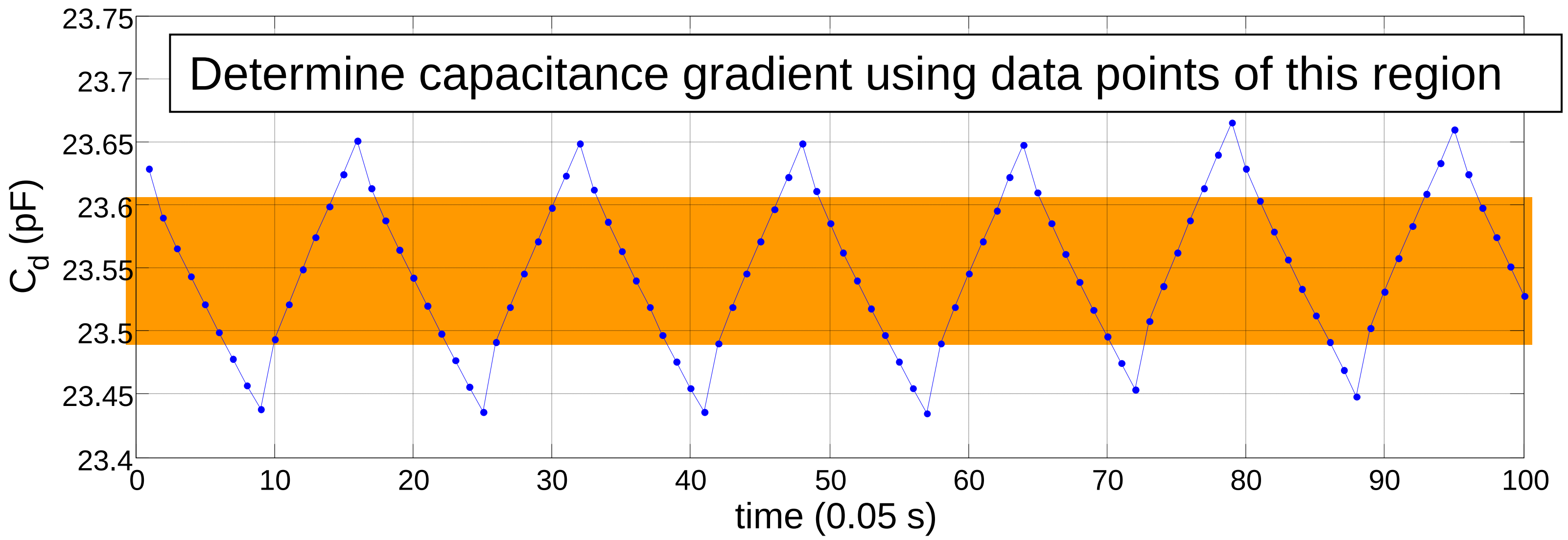
Deflection is maintained at zero by a FPGA based realtime controller (loop rate 200 kHz)

Capacitance gradient *dC/dx*

- Traceable measurement: calibrated capacitance bridge and optical interferometer.

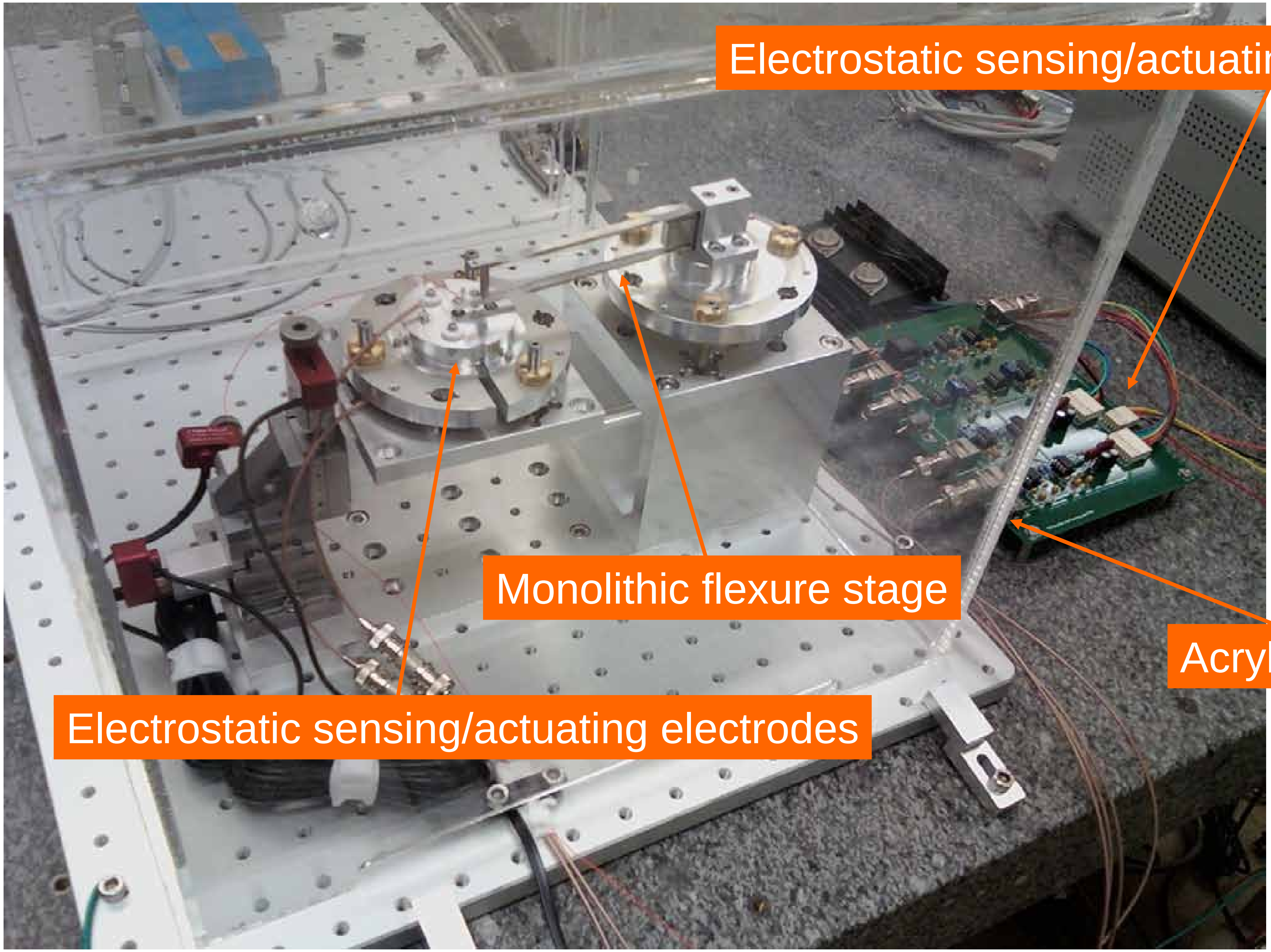


=> $dC/dx = (5.46 \pm 0.13) \times 10^{-8}$ F/m



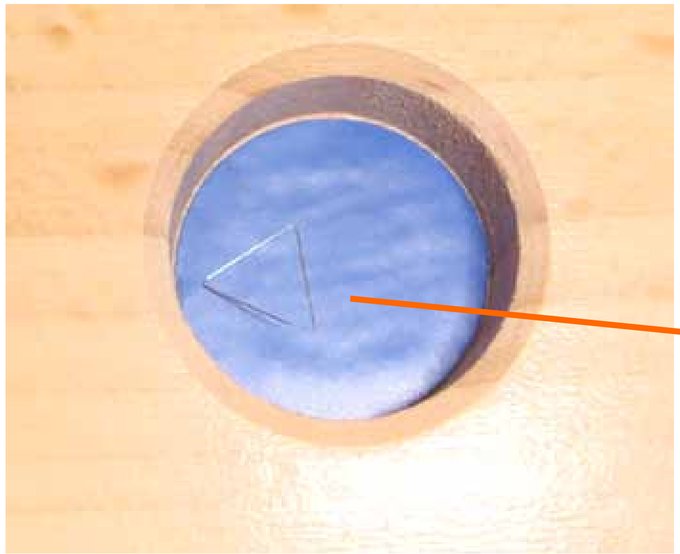
Average slope determined by the linear fit of more than 5000 capacitance to displacement data sets.

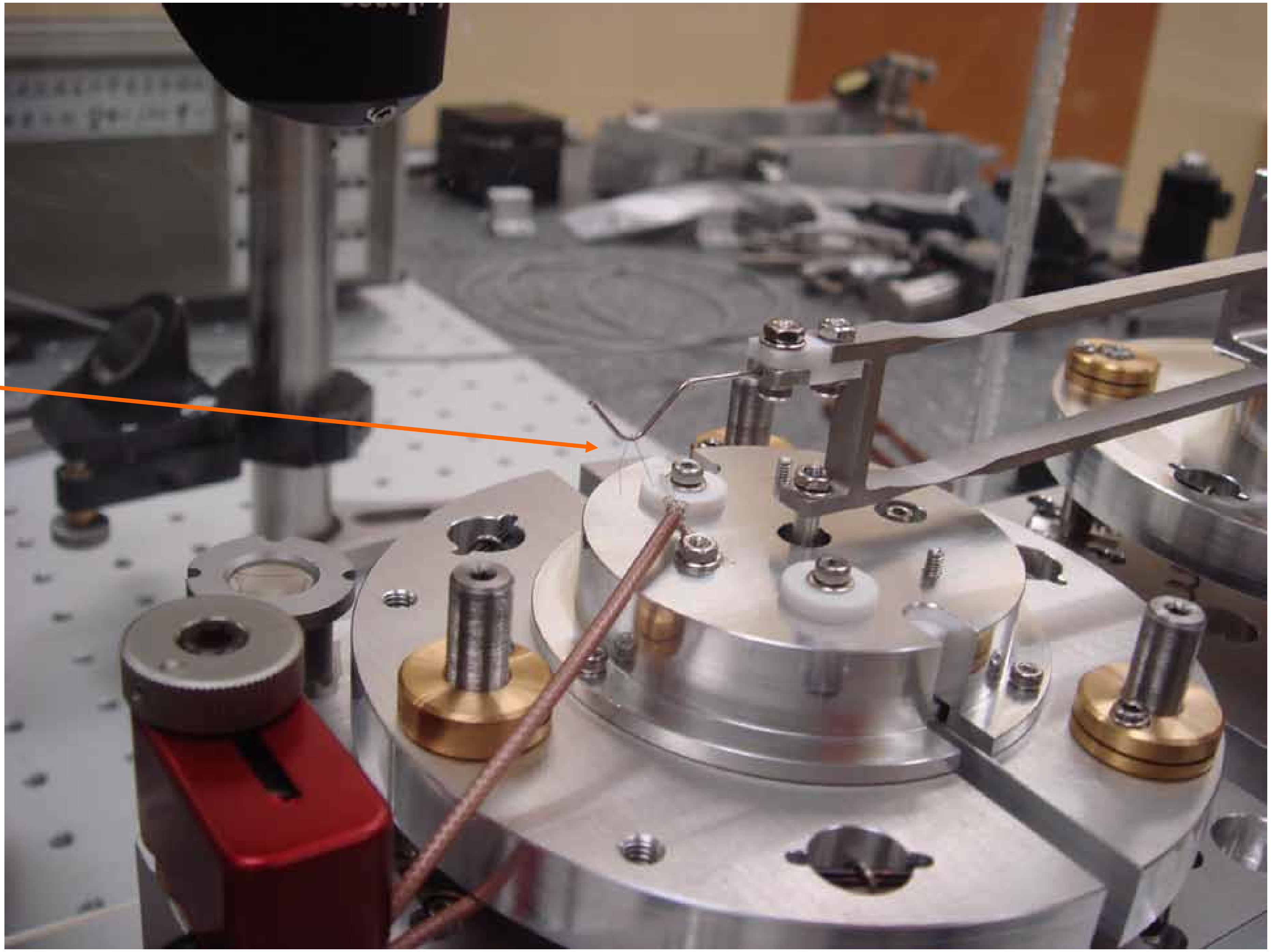
Force balance structure



1 mg weighing test (in air)

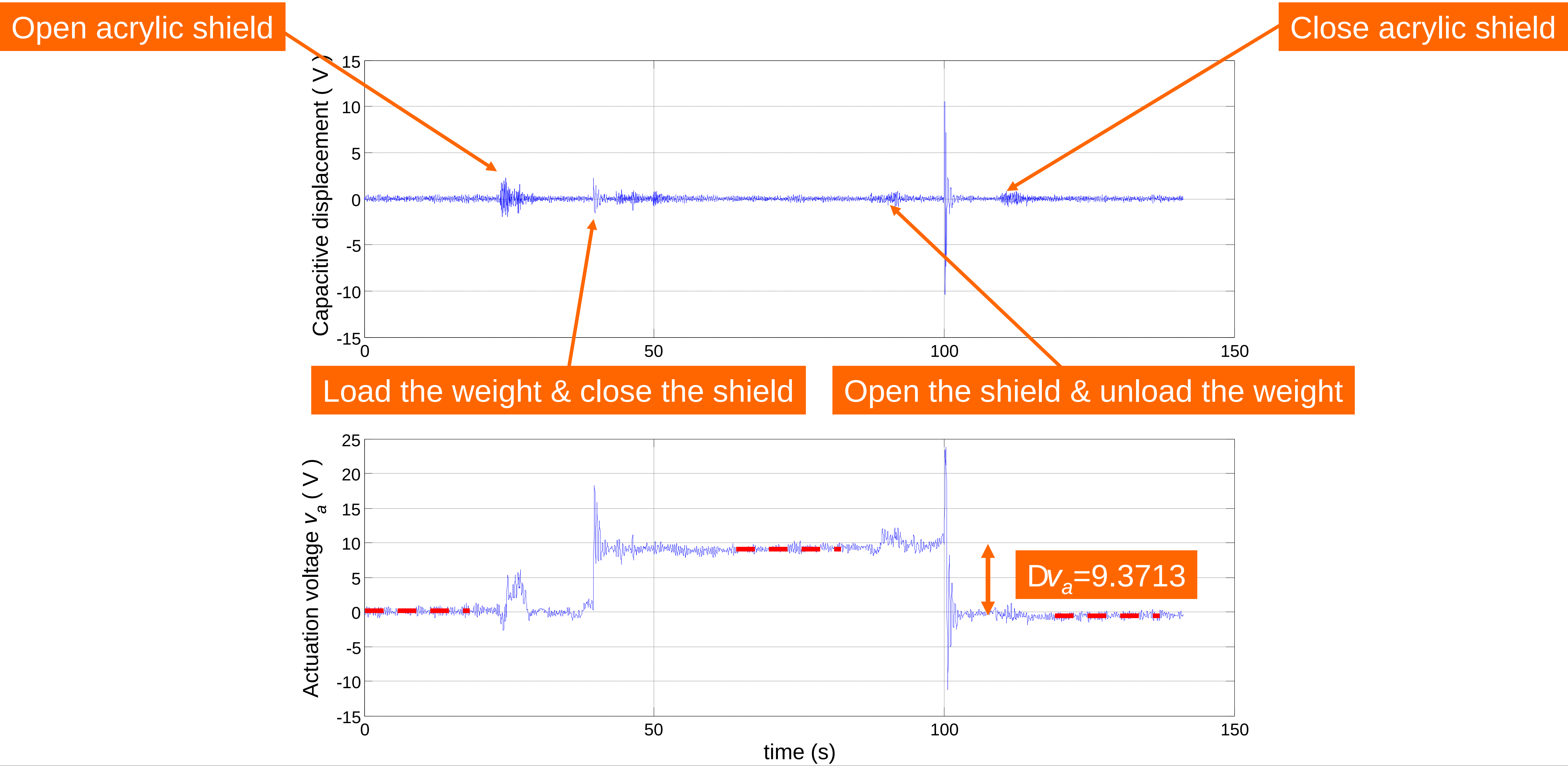
OIML class E1,
1 mg wire weight





1 mg weighing test result

- For the moment, mass is loaded by hand



1 mg weighing result

- $f_e = 2\, V_b\, v_a\, dC_1/dx|_{x=0} = \mathrm{m_e\, g}$

Measurement No.	f_e (mN)	Mass difference (mg)
1	9.7219	-6.9
2	9.802	1.3
3	9.8568	6.9
4	9.7089	-8.2
5	9.8504	6.3

Several tens of nanonewton

Mass difference is below 1%, test was performed in air and mass was loaded and unloaded by hand.

4.Summary

- Torsion pendulum facility and flexure stage with electrostatic force compensation introduced
- Radiation pressure force demonstrated, force sensitivity verified
- 1 mg weighing test in air completed, difference ~ several mg
- Measurement of universal gravitation is underway
- Future work: reduction of environmental noises and application to calibration of load cell and measurement of cantilever stiffness