Schweizerische Eidgenossenschaft
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Federal Institute of Metrology METAS

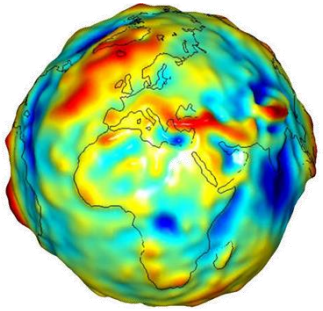
High precision gravity measurement

2nd International Workshop on Antimatter and Gravity

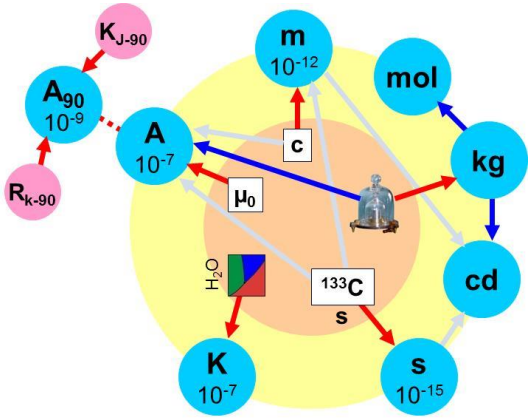
H. Baumann

1. Overview

- **Gravimetry**
  The measurement of the strength of a gravitational field



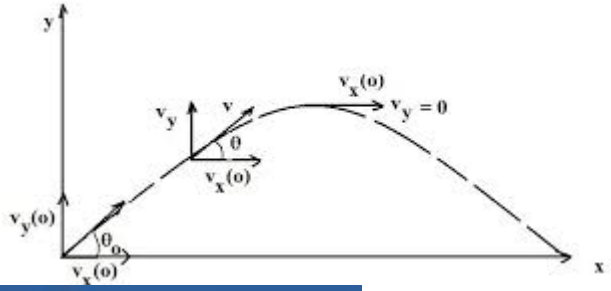
- **The future (SI)**
  The new International system of unit



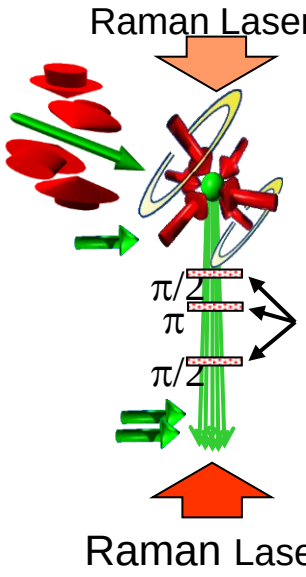
2. Absolute gravimeters

Simple pendulum

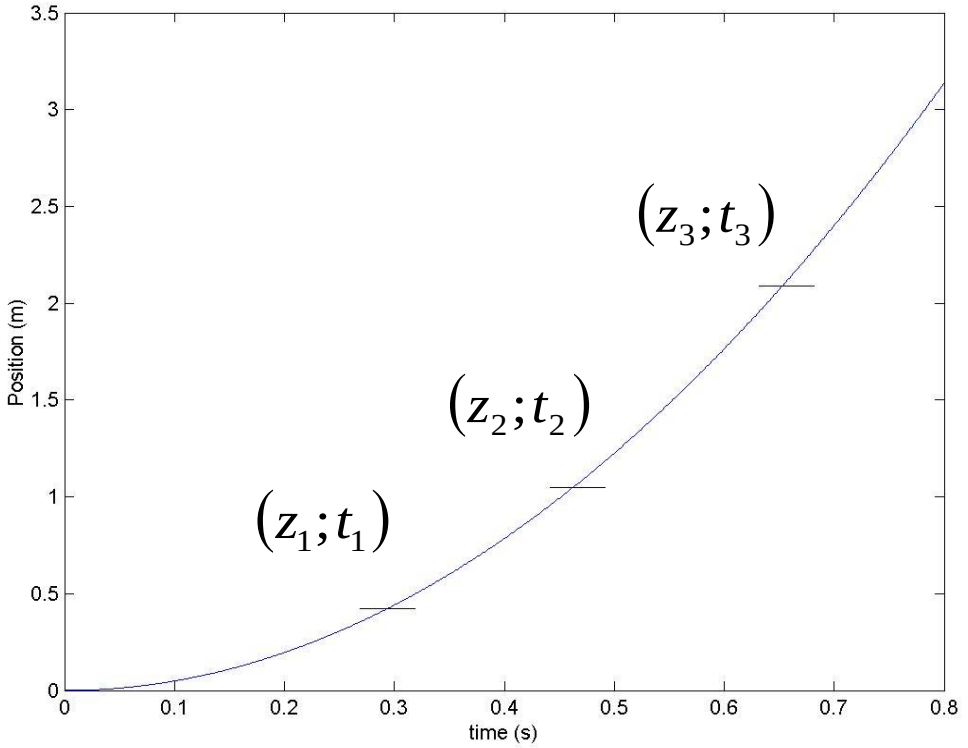
Ballistic gravimeters



Cold atoms gravimeters

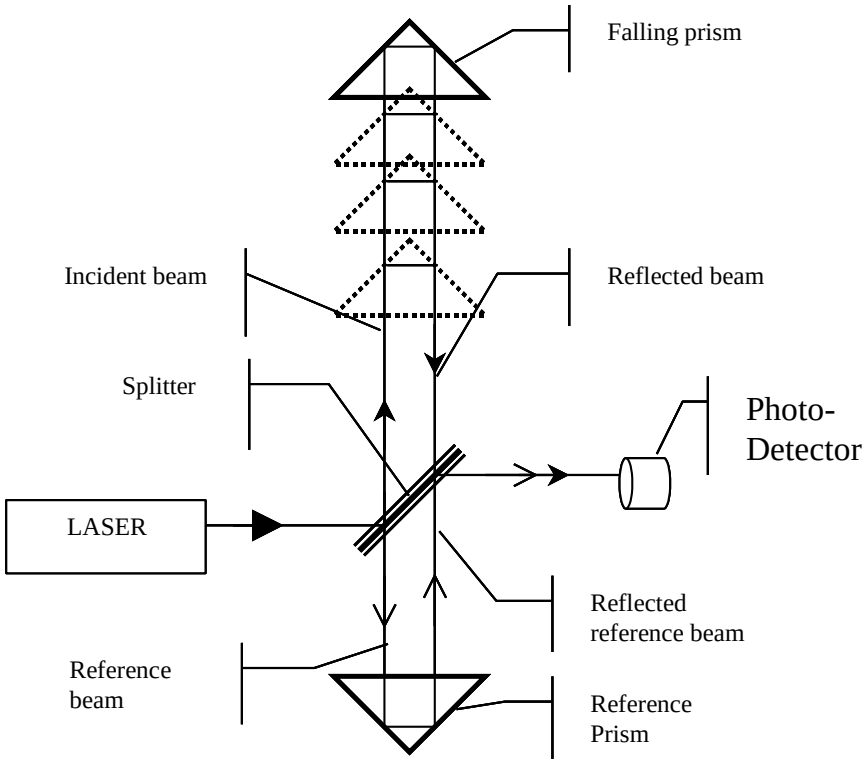


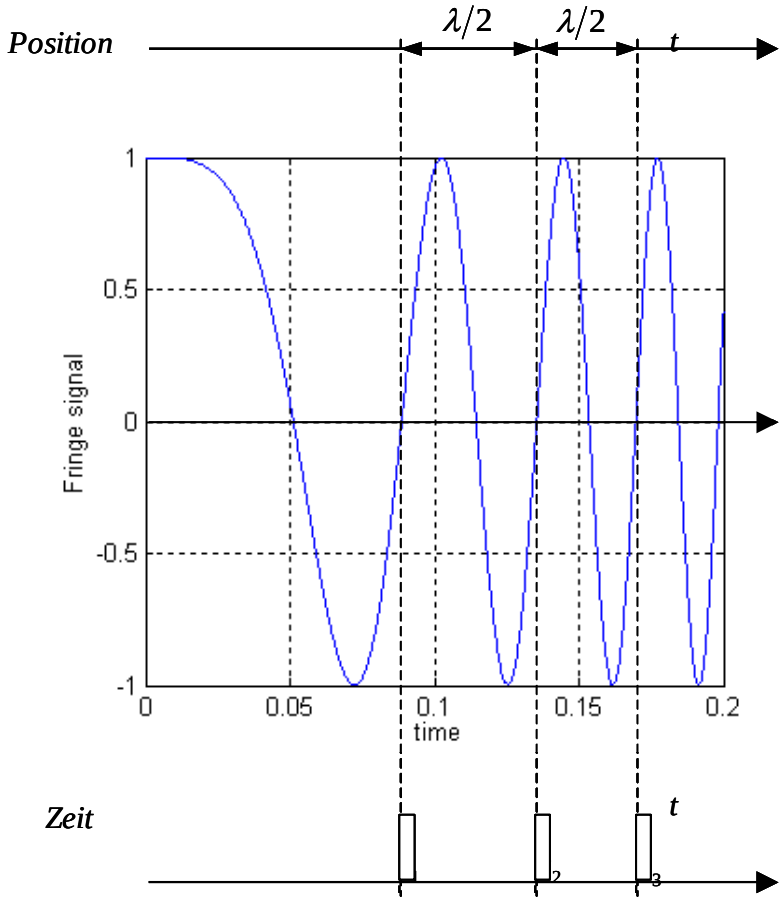
3. Ballistic gravimeter



$$\Rightarrow \quad g = 2 \cdot \frac{(z_3 - z_1)(t_2 - t_1) - (z_2 - z_1)(t_3 - t_1)}{(t_3 - t_1)(t_2 - t_1)(t_3 - t_2)}$$

4. Ballistic gravimeter, working principle

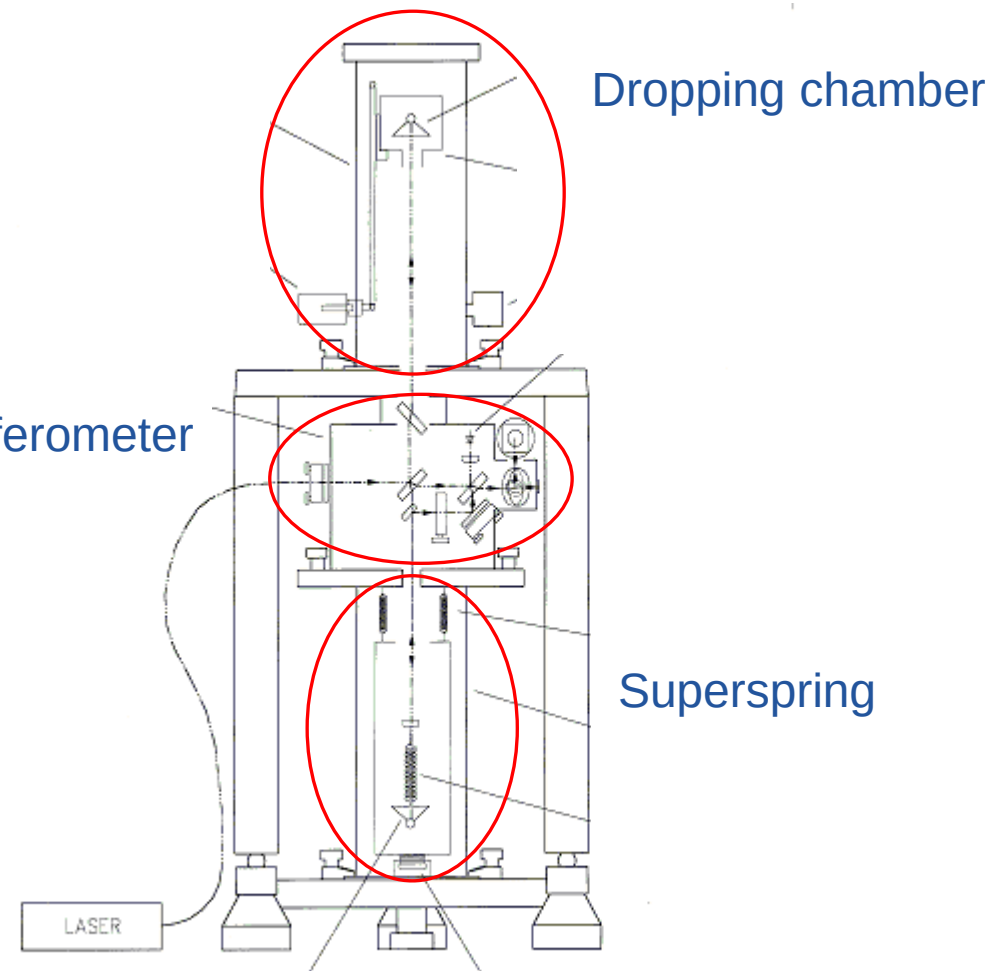




5. Free Fall Gravimeter

Source: Microg-Lacoste

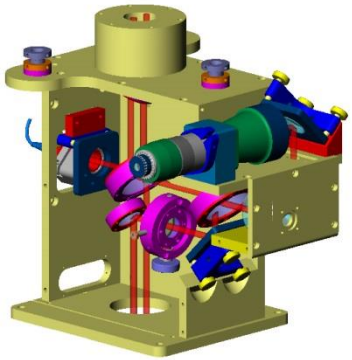
FG5 Gravimeter:

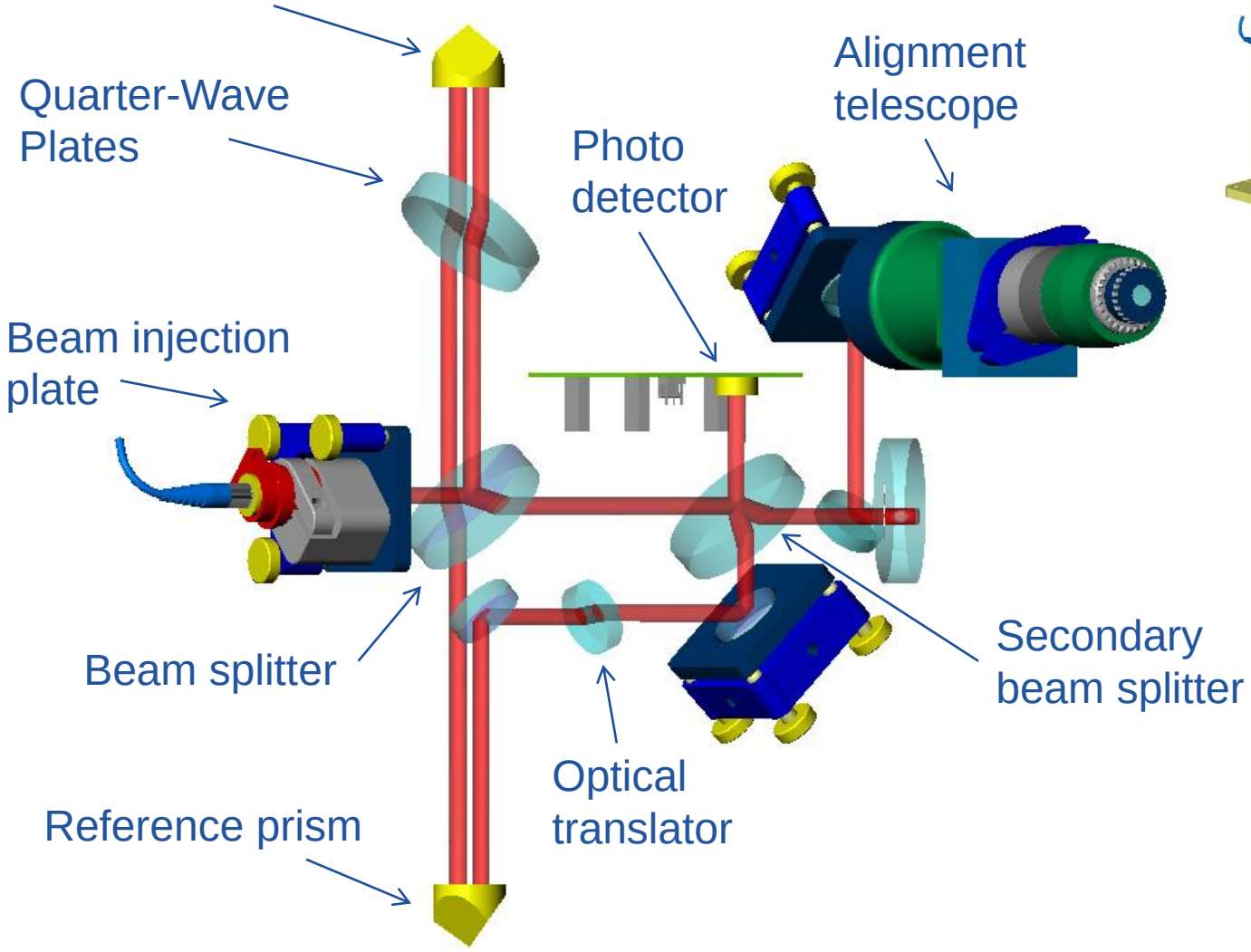


6. FG5 Gravimeter

Source: Microg-Lacoste

Interferometer: Mach-Zender type

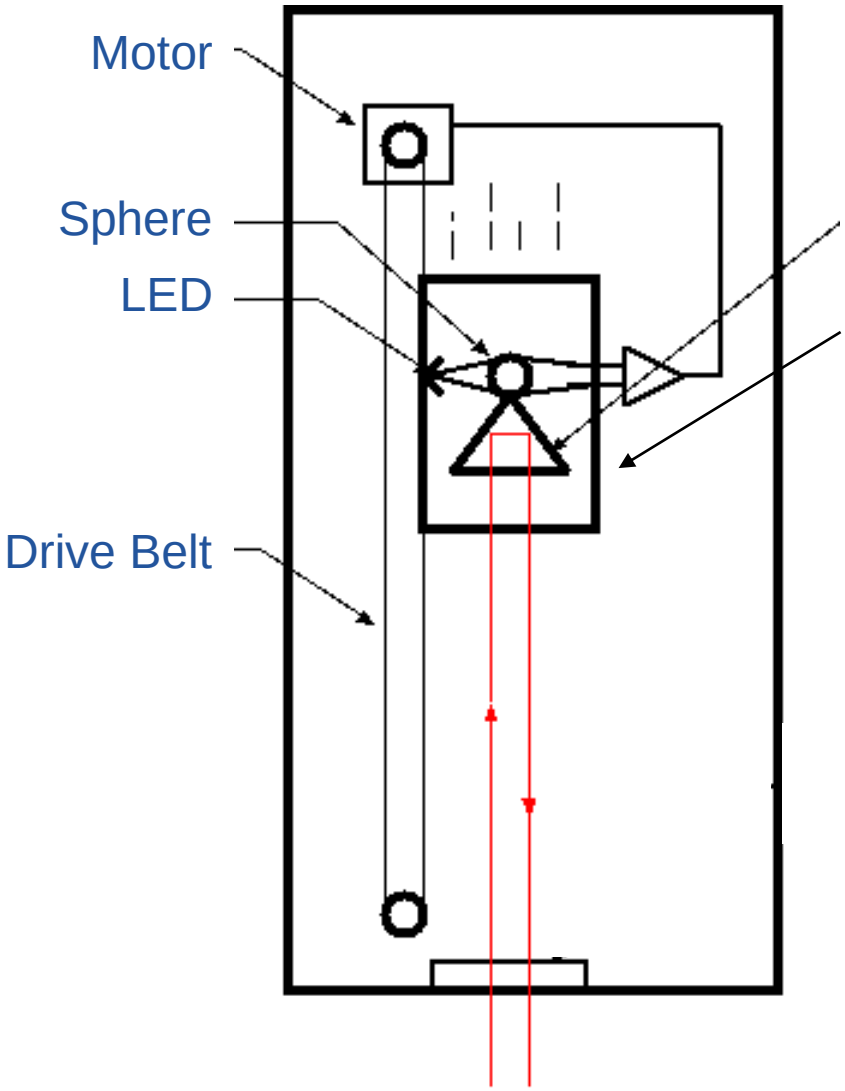




7. FG5 Gravimeter

Source: Microg-Lacoste

Dropping chamber: Dropping chamber (Vacuum ~ 10^{-4} Pa)

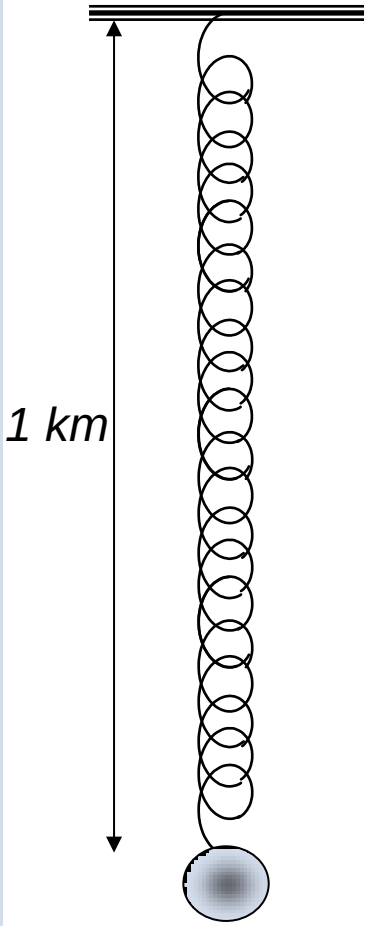


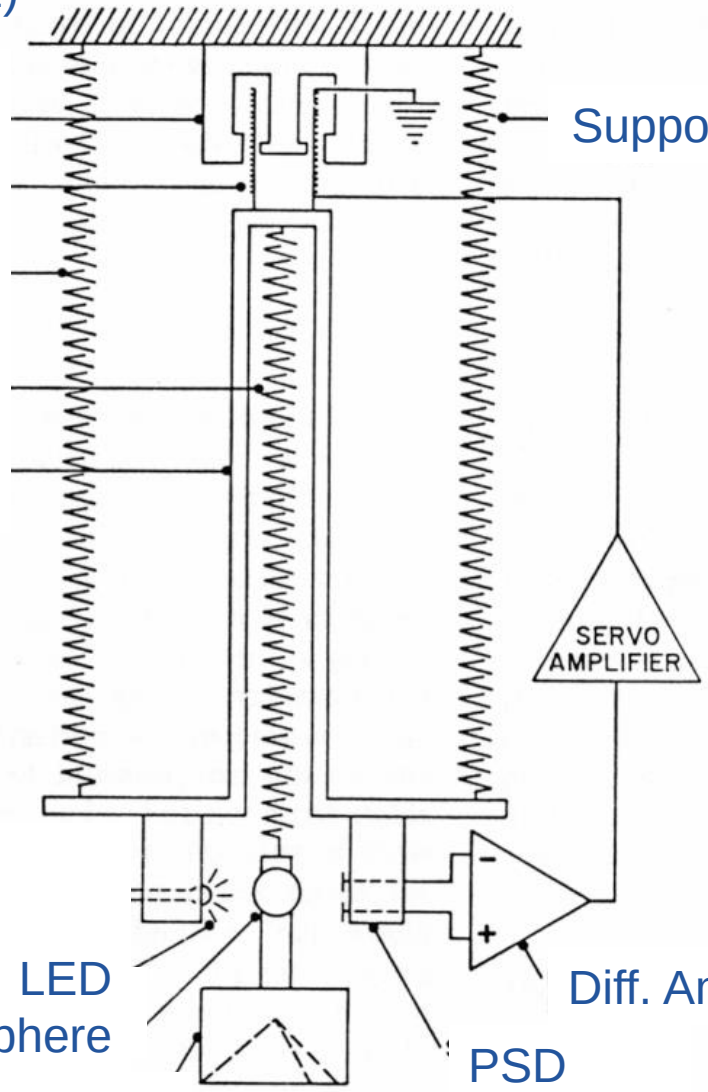
- Reduces drag due to residual gas molecules.
- Follows the dropped corner cube, gently arrest and lift it
- Shields the corner cube from external electrostatic forces

8. FG5 Gravimeter

Source: Microg-Lacoste

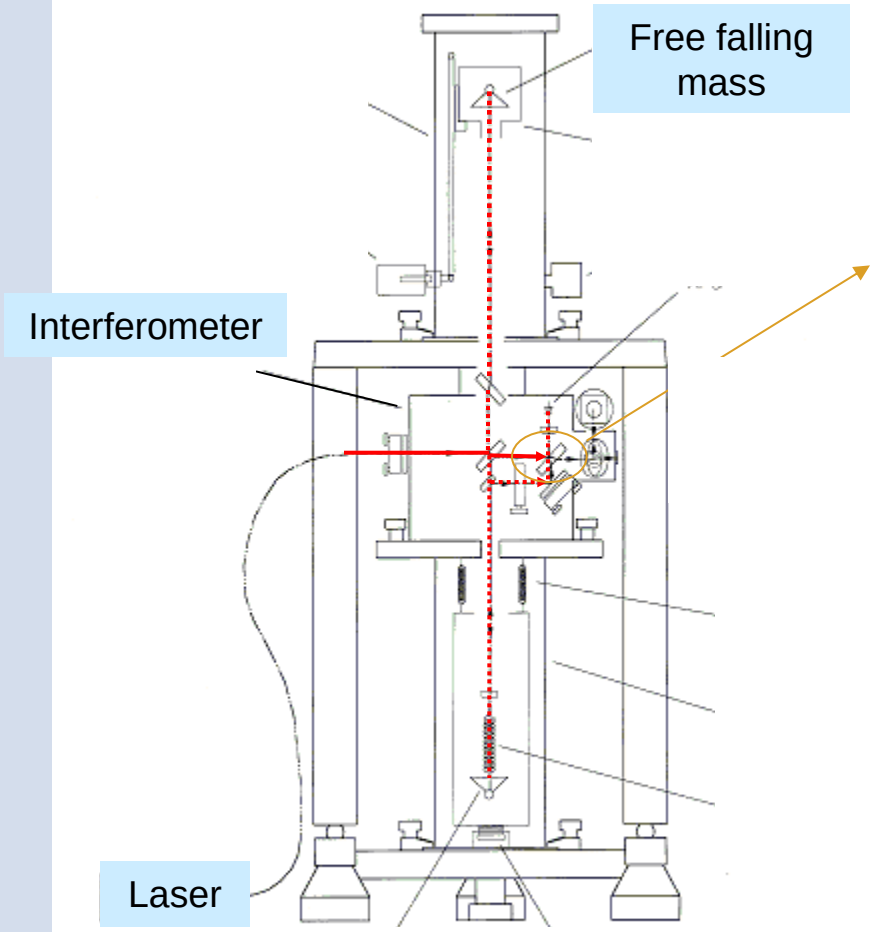
Superspring: Damping microseismic noise (free period ~ 60 s, f_c ~ 0.017 Hz)

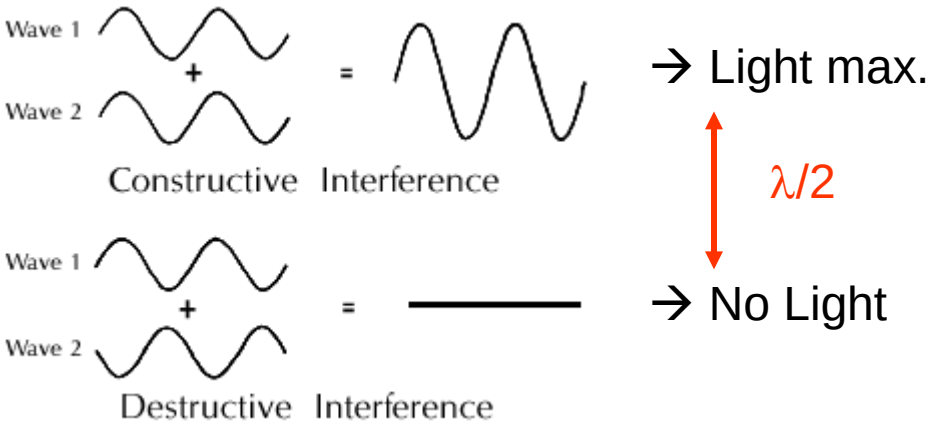




Source: Microg-Lacoste

General overview:



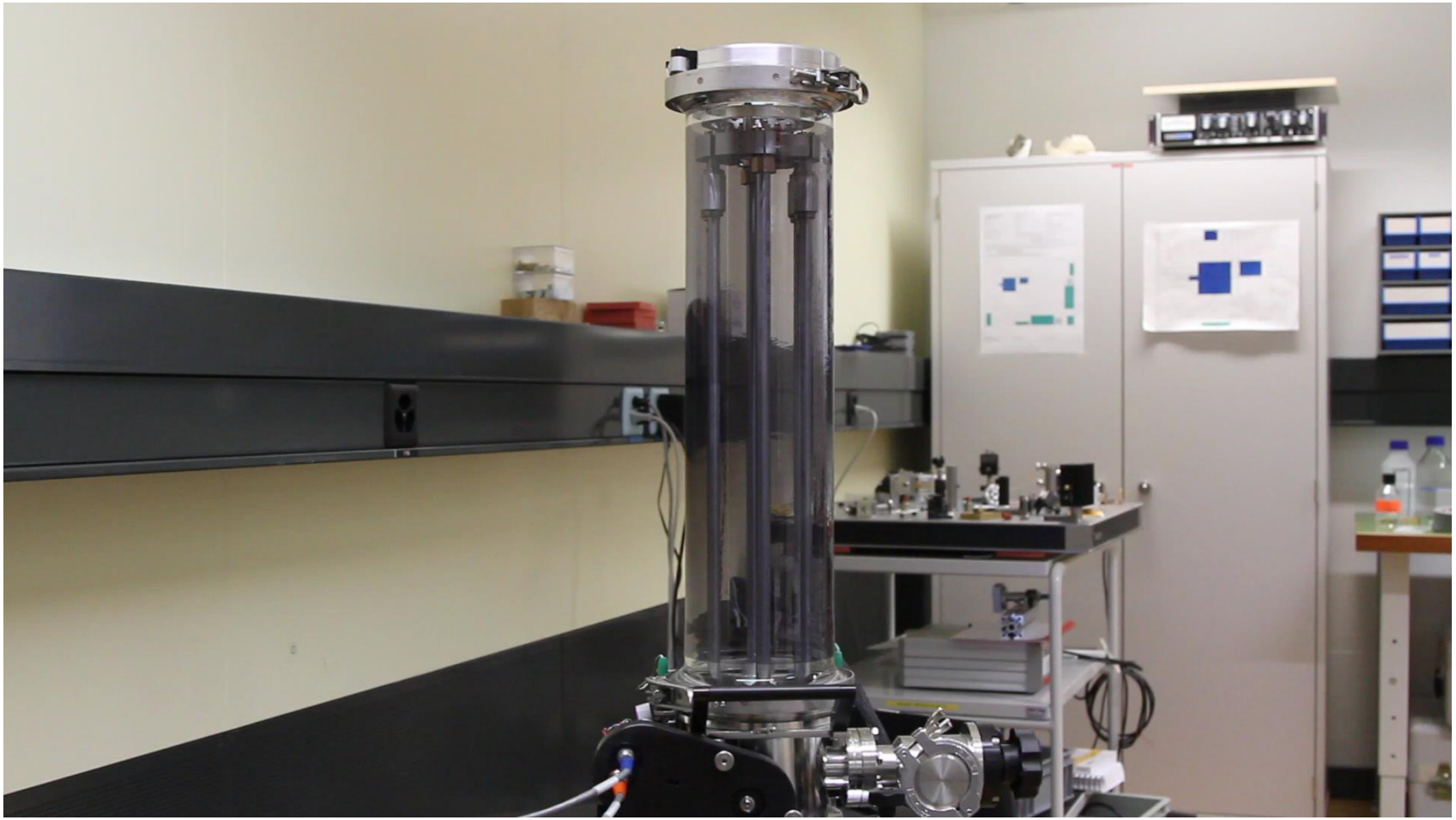


- At present, the fringes are produced from the light of a He-Ne laser (red light @ 633 nm)
- Free fall on 20 cm during 0.2 s : 640'000 fringes, with frequency sweeping from 0 to 6 MHz.
  In practice, one takes 1 fringe / 1000
- The time intervals between the occurrence of each fringe are measured by a Rb oscillator (or Cs if available)

9. FG5 Gravimeter

Source: Microg-Lacoste

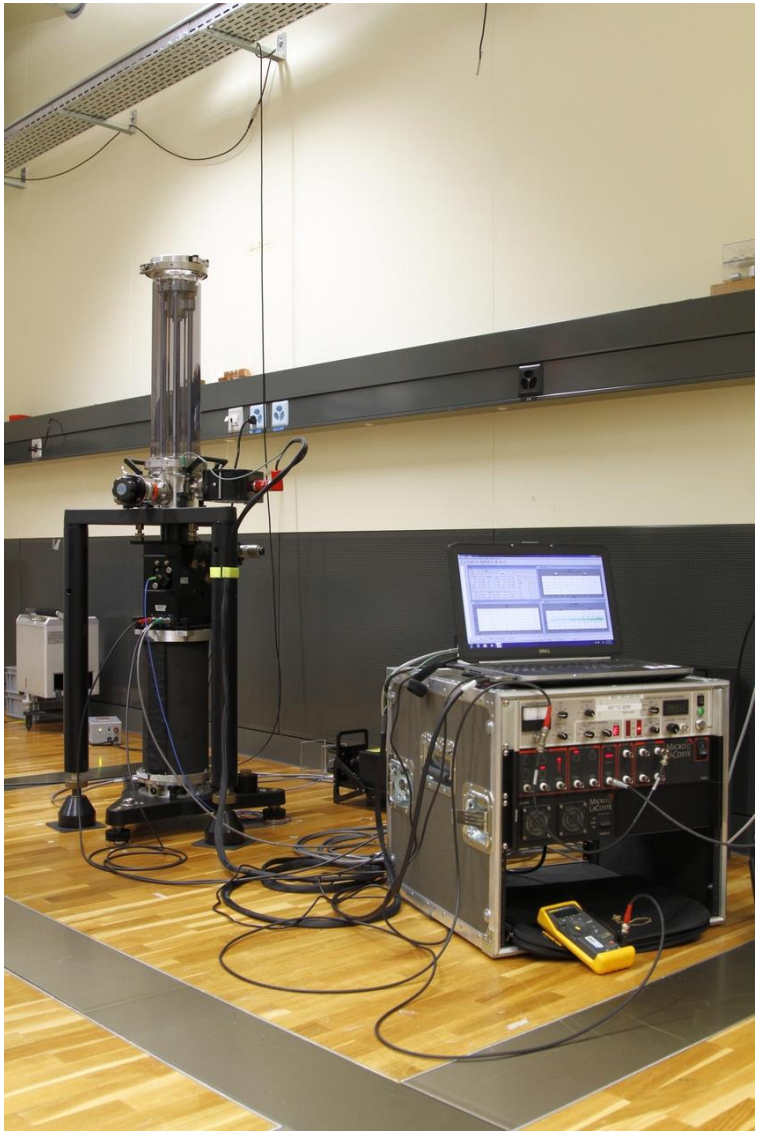
General overview:



9. FG5 Gravimeter

Source: Microg-Lacoste

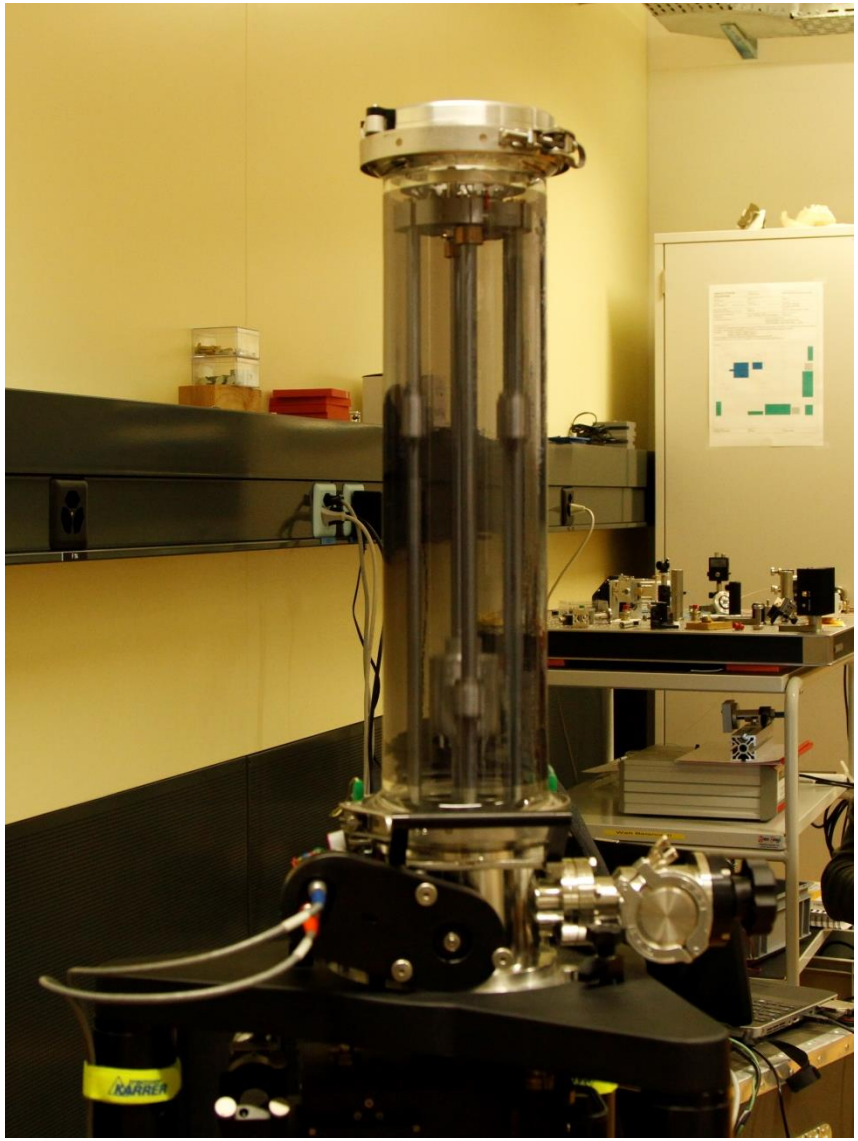
General overview:

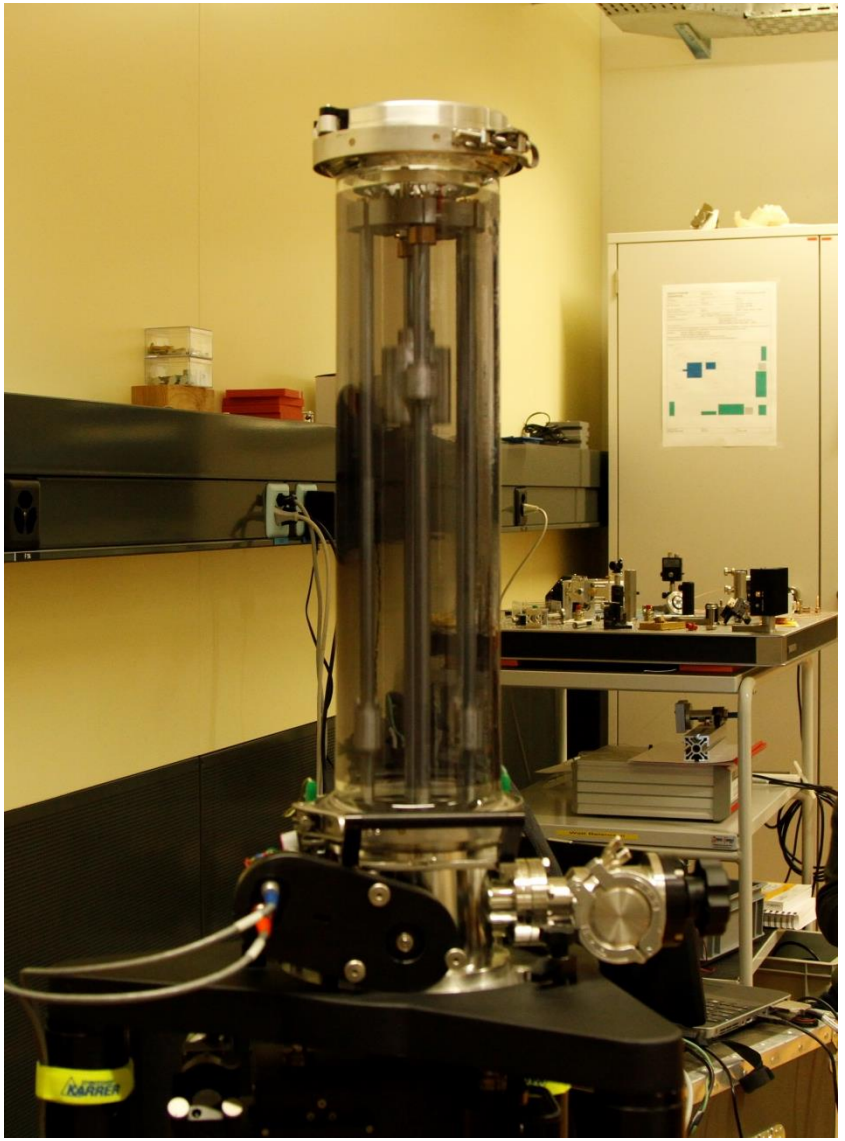


9. FG5 Gravimeter

Source: Microg-Lacoste

General overview:





10. *g* determination

Source: Microg-Lacoste

- 1 fringe = $\lambda/2 = x_i$
- For each $\boldsymbol{x_i}$, a measured time $\boldsymbol{t_i}$,
- The following function is fitted to the data $\boldsymbol{x_i}$, $\boldsymbol{t_i}$:

$$x_i = x_0 + v_0\tilde{t} + \frac{g_0\tilde{t}_i^{\,2}}{2} + \frac{1}{6}\gamma v_0\tilde{t}_i^{\,3} + \frac{1}{24}\gamma g_0\tilde{t}_i^{\,4}$$

$$\tilde{t} = t_i - \frac{(x_i - x_0)}{c}$$

$\boldsymbol{x_i}$, $\boldsymbol{t_i}$, i = 1, …,700

- x_0 the initial position,
- v_0 the initial velocity,
- $\boldsymbol{g_0}$ *the initial acceleration*.
- γ is the vertical gravity gradient
- c the speed of light,

g with an uncertainty of 1 part in 10^9 or some µGal

1 Gal =1 cm/s^2

11. Gravity correction and systematic errors

Correction:

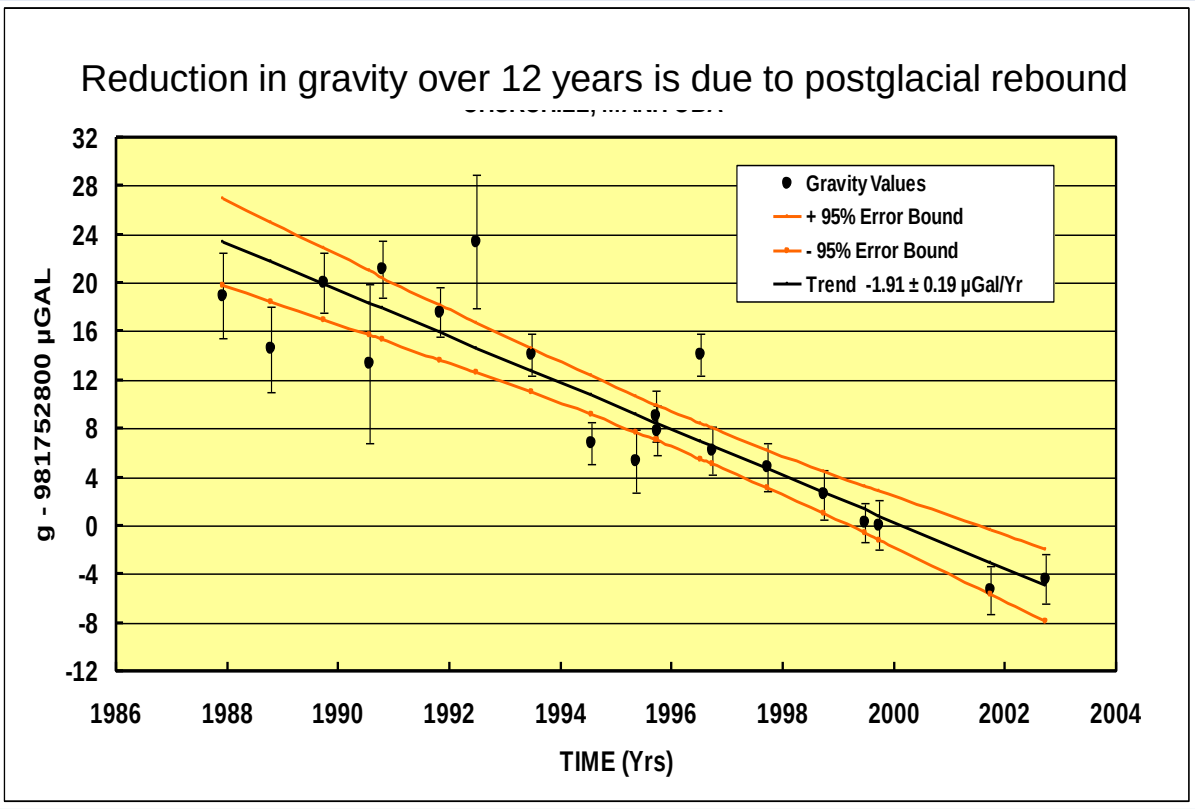
- Earth Tides (+/- 150 µGals)
- Ocean Loading (+/- 3 µgal in Brussels)
- Barometer (- 0.3 µgal / hPa)
- Polar motion (+/- 5 µgal)
- Gradient (~ 300 µgal/cm)
- Speed of Light (~ 10 µgal)

Errors:

- Common Error Sources
  - Verticality: 9 arcsec = 1µGal
  - “1 spot” = 4µGal
- Environmental Errors
  - Water Table: 2.5 cm =1µGal
  - Air Pressure: 1mBar = 0.3-0.4µGal

Geophysics / Geodesy:

- Mining Exploration
- Oil & Gas Exploration
- Reservoir/Aquifer
- Monitoring/Management
- Tectonics/Crustal Motion
- Subduction/Uplift Zones
- Vulcanology
- Sea Level Change
- Fault Lines/Earthquake Studies
- Tidal Studies
- Nuclear Waste Management
- True Surface Geoid

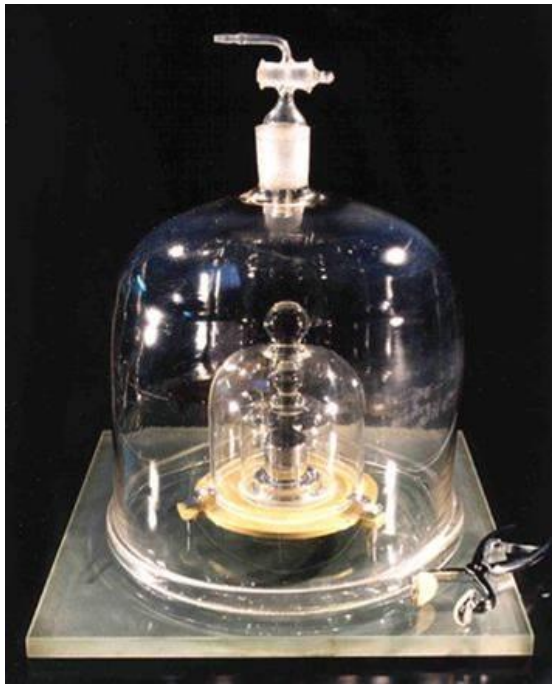


13. Applications

Metrology:

- Primary standard for *g*
- Calibration of Instruments:
  - Load Cells
  - Precision Relative Gravity Meters
  - Spring Type
  - Super-conducting Type

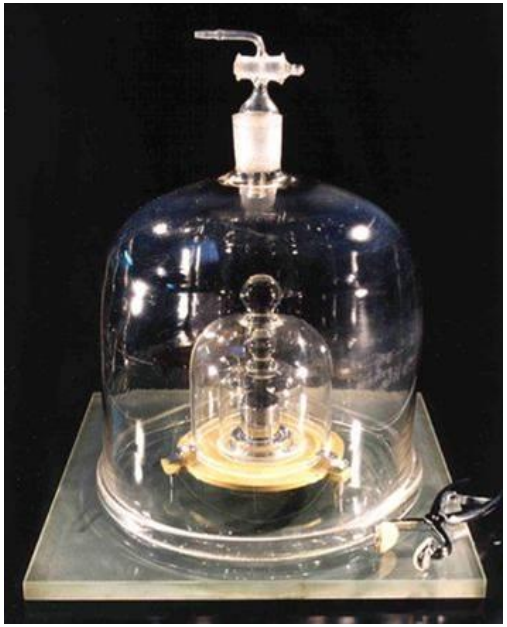
- Define ‘G’
- Definition of the unit of masse



14. One of the last metrological challenge

Today's definition CGPM, 1901

"The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram."

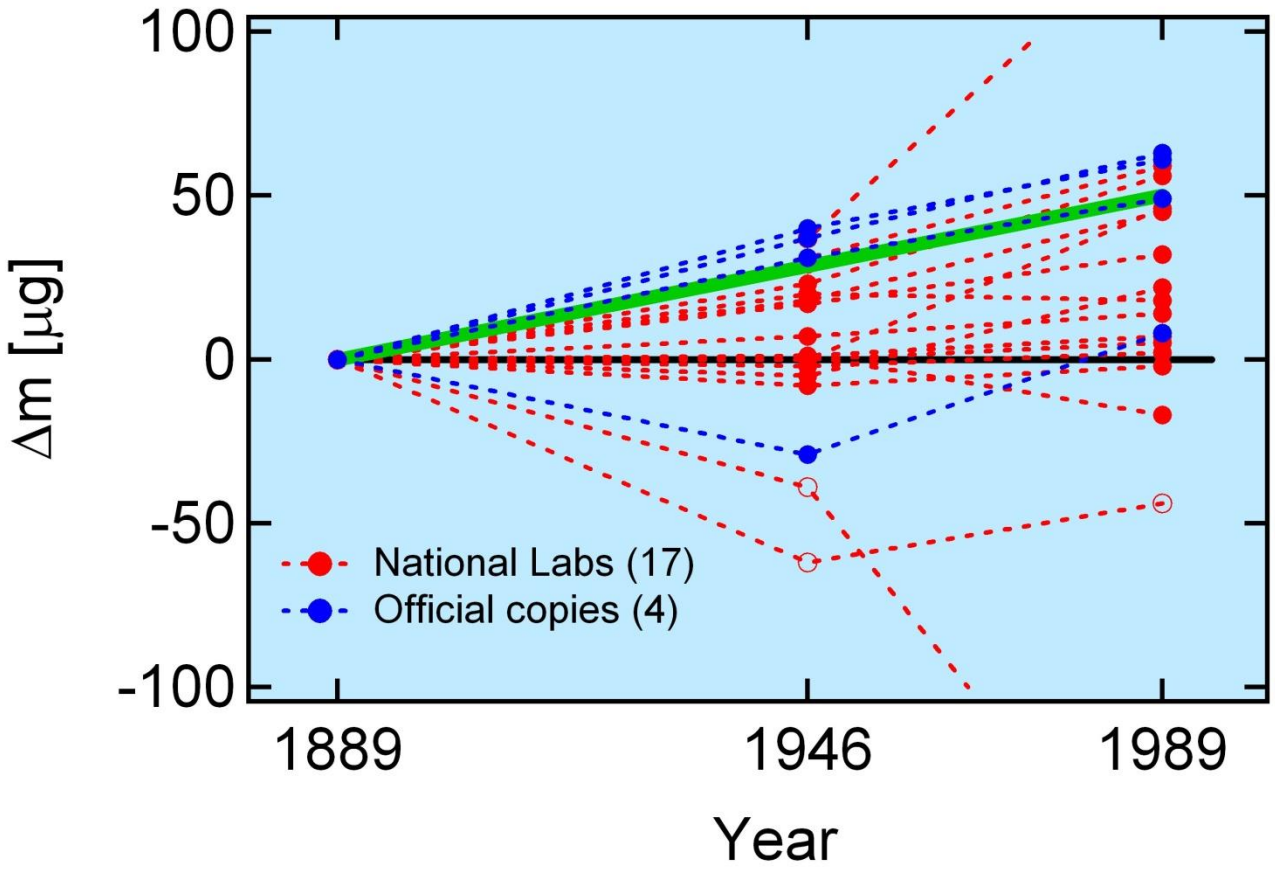


- 90% Platinum, 10% Iridium alloy manufactured in 1878 (Johnson-Mathey),
- cylindrical shape: h = Ø = 39 mm,
- stored in a safe, in ambient air at BIPM,
- copies (official (6) + for members of MC).

Weakness of the present definition:

- local,
- uniqueness,
- exposed to damage,...

15. Verifications of National Prototypes of the kg



Average mass drift of National Prototypes of the kilogram against the IPK:

~ 50 μg / 100 years

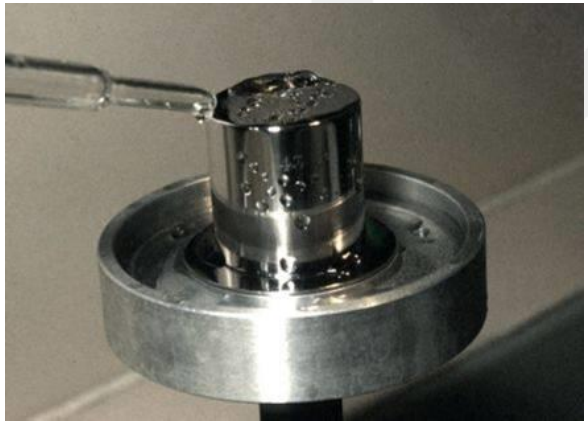
‘Improved’ definition

"The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram." (CGPM, 1901)

... immediately after cleaning and washing by a specified method (mise en pratique, CIPM 1989).

CIPM 1989: Cleaning procedure

1. Wash with ethanol + ether + chamois leather
2. Rinse with steam



17. The Situation in the mass laboratory

- Prototype #89 (2004)

  u_r **5 µg** (k=2)

- Comparison 2 x 1 kg (Pt-Ir)

  u_r **<1 µg**

1 part in 10^9 !!

- Comparison 2 x 1 kg (Pt-Ir vs Stainless steel)

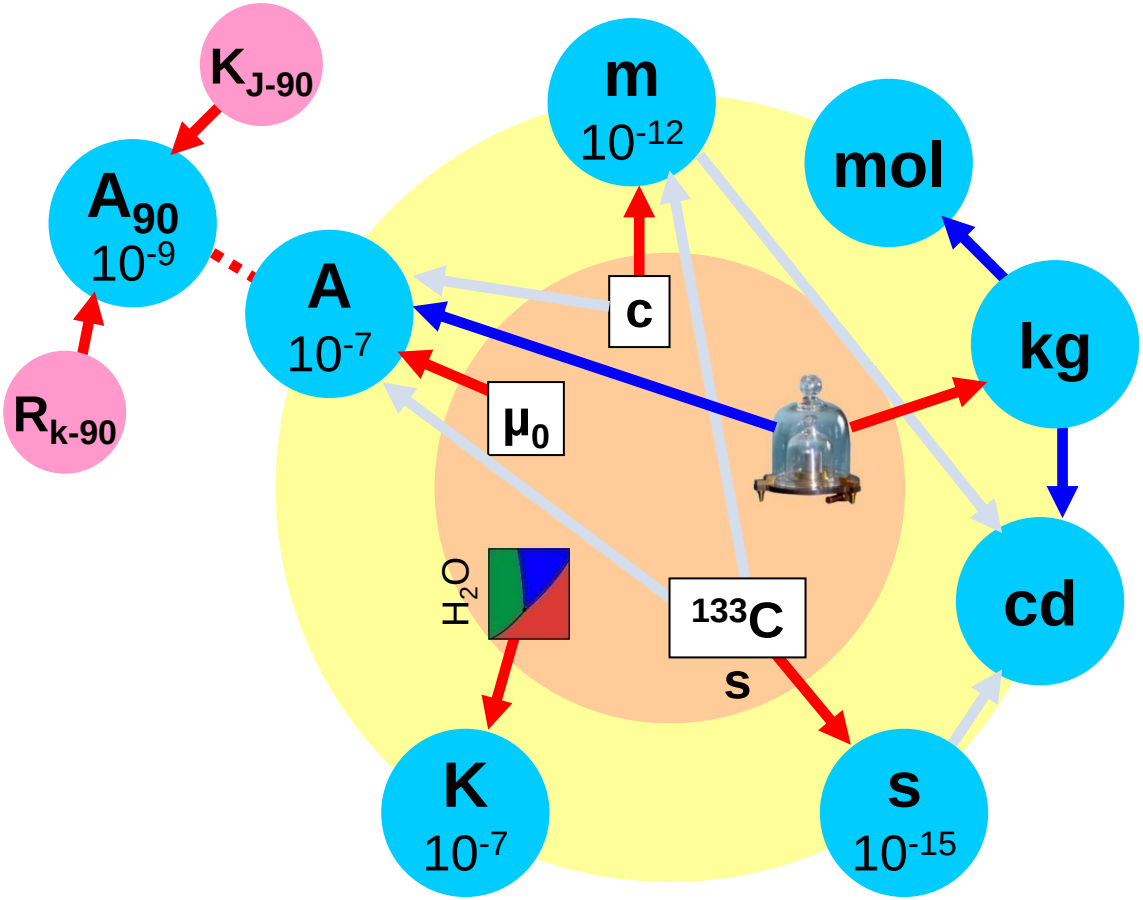
  u_r **~10 µg**

- In 1889: comparison 2 x 1 kg (Pt-Ir)

  u_r **~10 µg**

18. SI

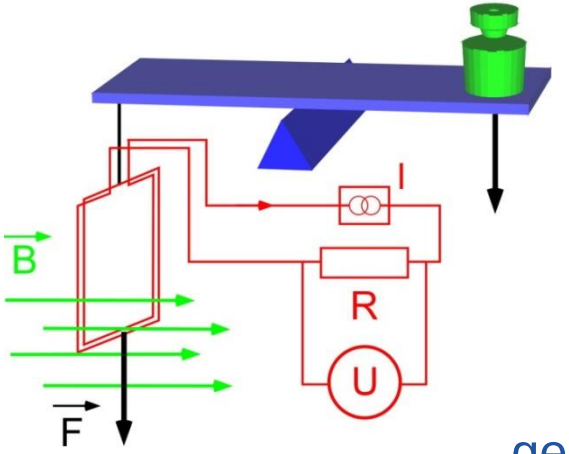
- The International System of Units (SI)



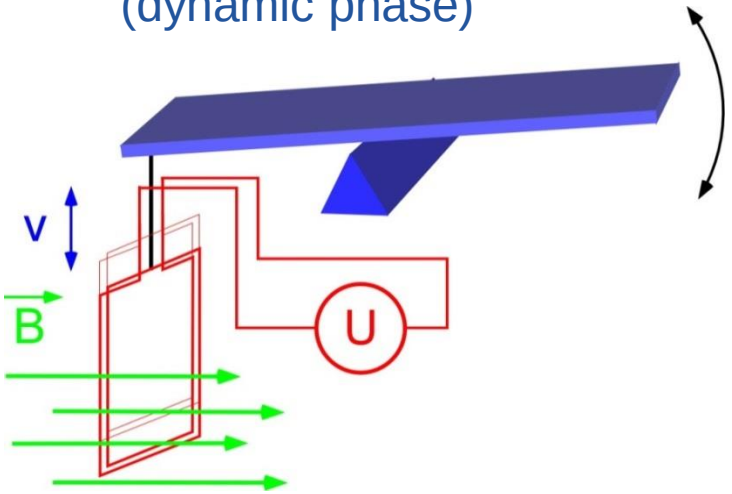
19. The Watt Balance working principle

Linking the mass to the Plank constant h

Force measurement
(static phase)



Induction measurement
(dynamic phase)



geometrical factor

$$F = I\int B\cdot dl = mg \qquad U = v\int B\cdot dl$$

$$\Rightarrow UI = mgv$$

Electrical power — Mechanical power

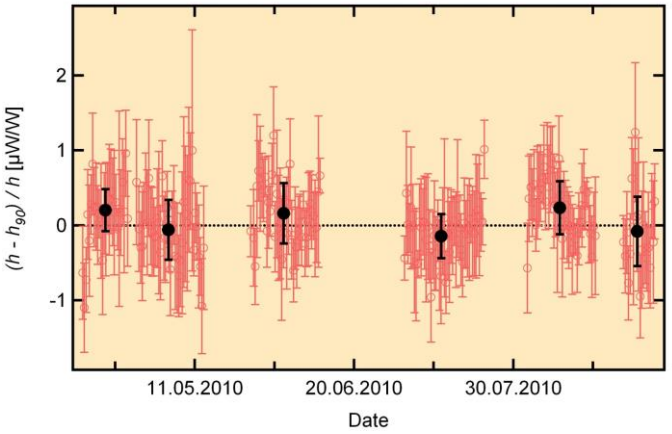
$$m = C\,\frac{f_{J1}f_{J2}}{g\,v}\,h$$

20. Determination of the Planck constant

h value WBM I

Measurement conditions:

- 100 g AuCu
- p(air) = const
- 3400 h

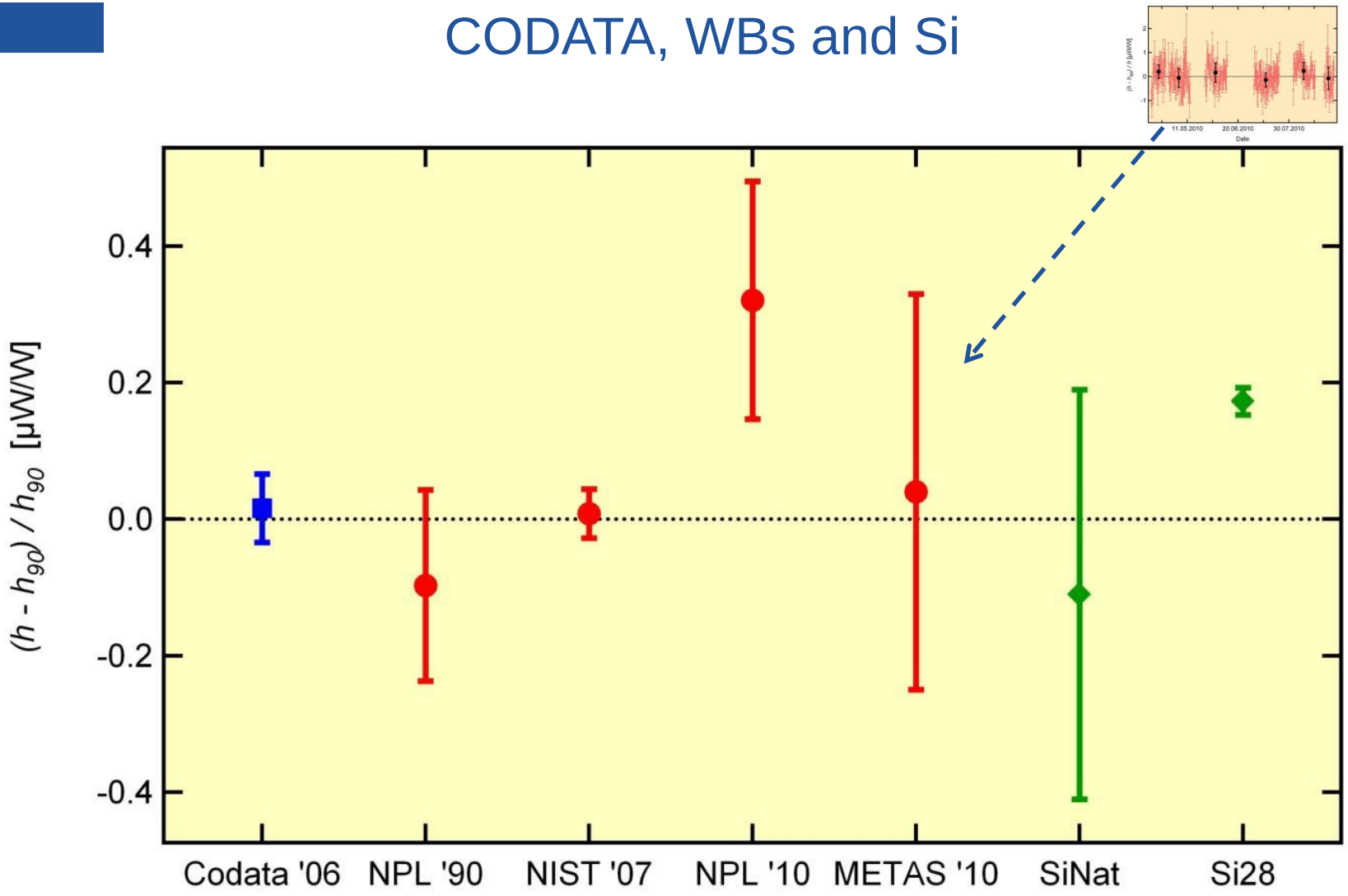


$h = 6.626\,069\,1(20)\cdot10^{-34}$ Js $[0.29\cdot10^{-6}]$

Metrologia **48**, 133-141 (2011)

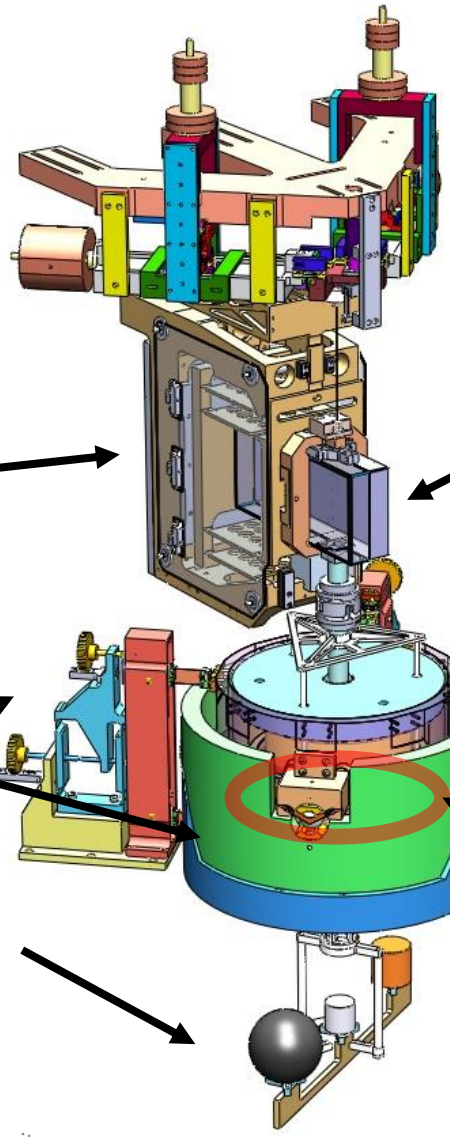
21. The Planck constant today

CODATA, WBs and Si



22. BWM II: the new design

Design overview



Driving stage

Translation stage

B field orientation system

Test mass & exchanger

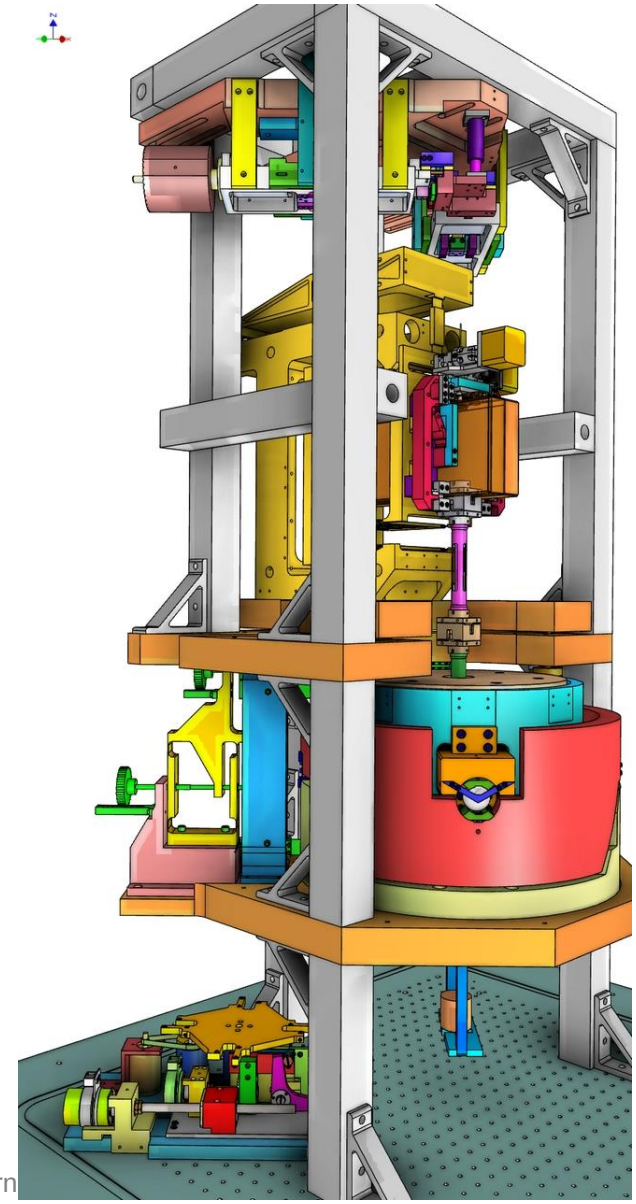
Mass comparator

Magnet

Coil

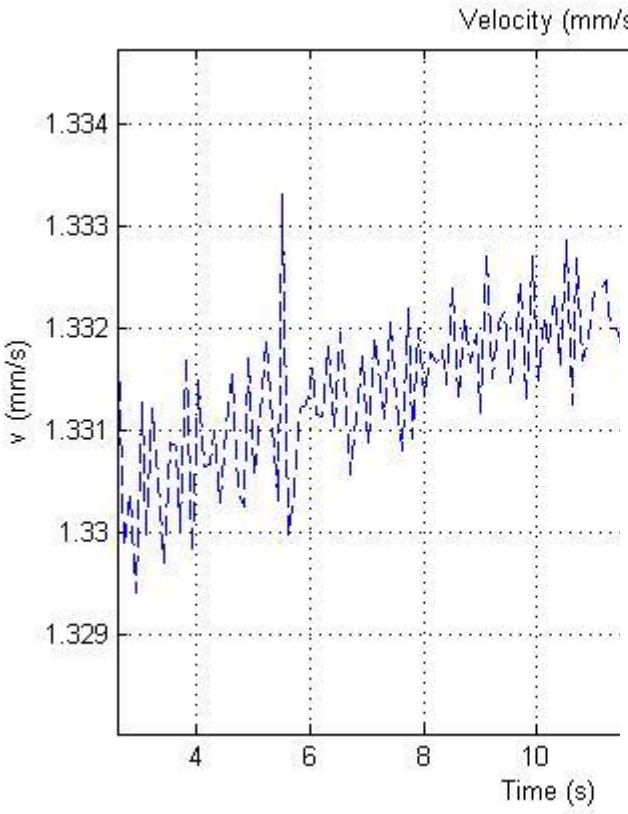
23. BWM II

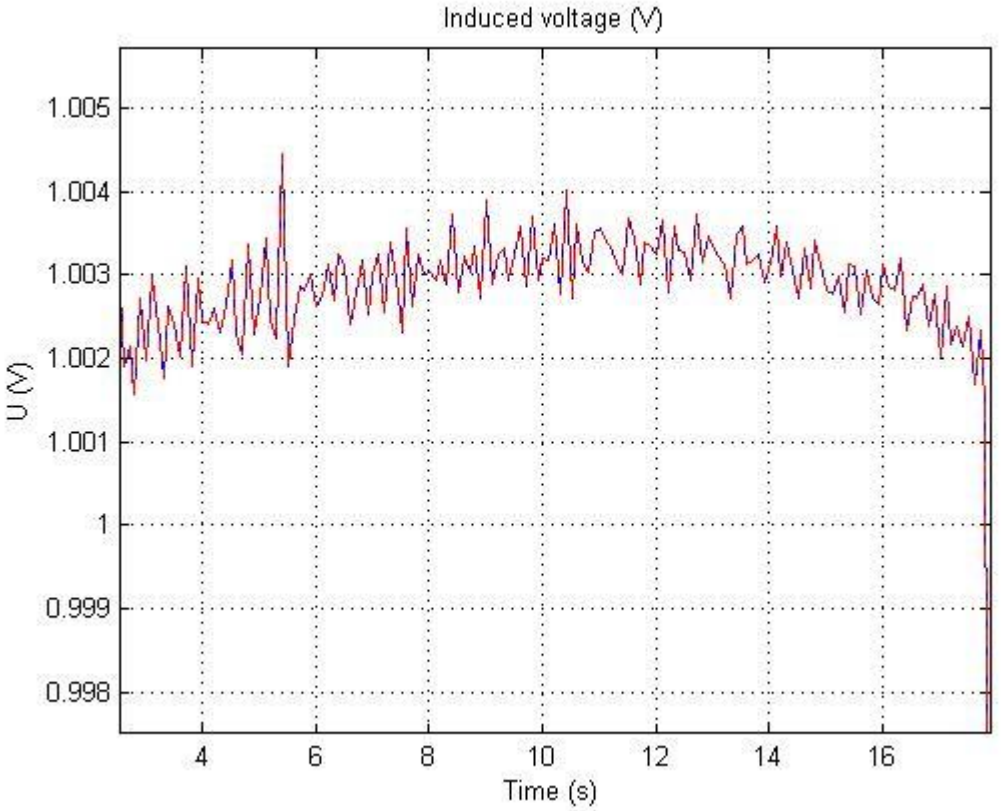
In the lab



24. Very first measurements

Induced voltage / velocity





Thank you very much

Any questions