CCM Workshop, May 17, 2019, BIPM

Realization of small mass, force and torque measurements based on the new definition of the kilogram

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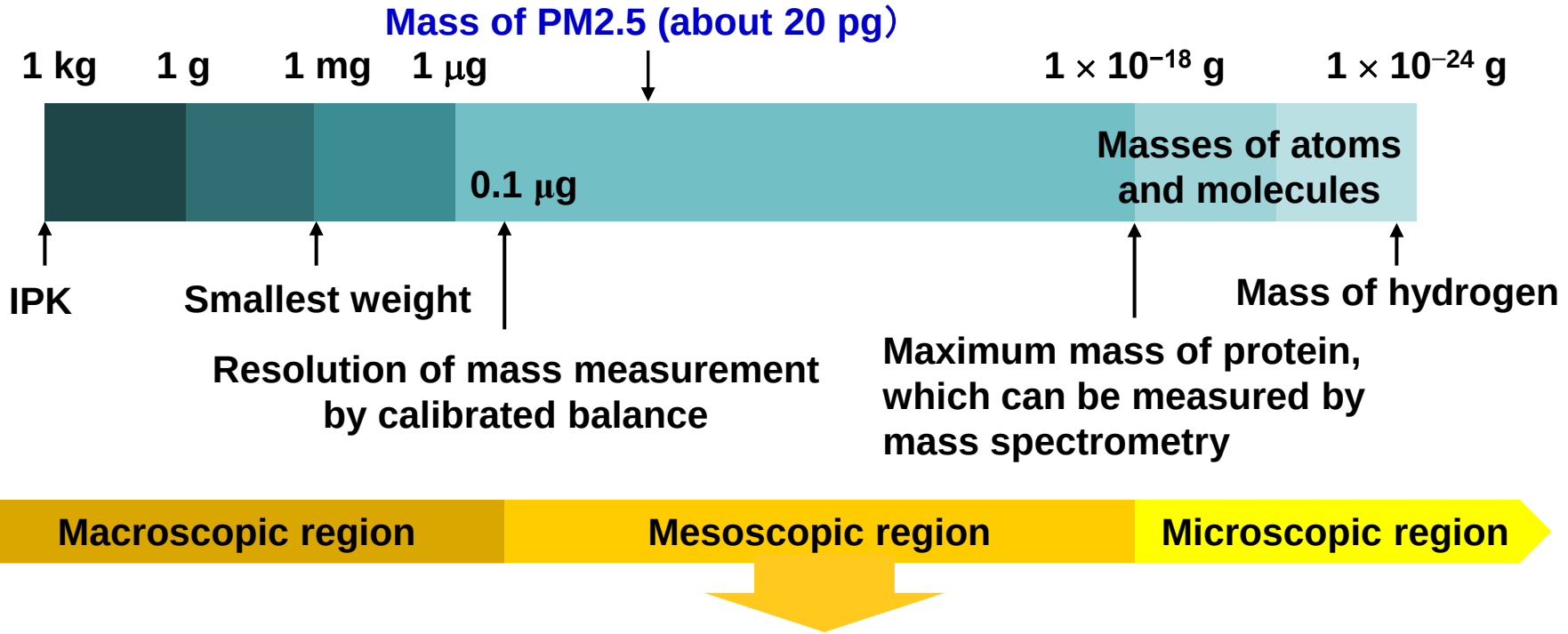
- **Principle of small mass, force and torque measurements using the new definition of the kilogram**
- **Their possible applications to industry**

26th CGPM, November 16, 2018

Advantage of the new definition of the kilogram

- Like the redefinition of the metre defined by the speed of light, the kilogram will be realized from the universal constant.
- A new application for a small mass standard



Traceable mass measurement is still not established in this region.

Principle of the small force measurement

Kilogram (kg): Planck constant h

Ampare (A): elementary charge e

Voltage: Josephson effect ($2e/h$)

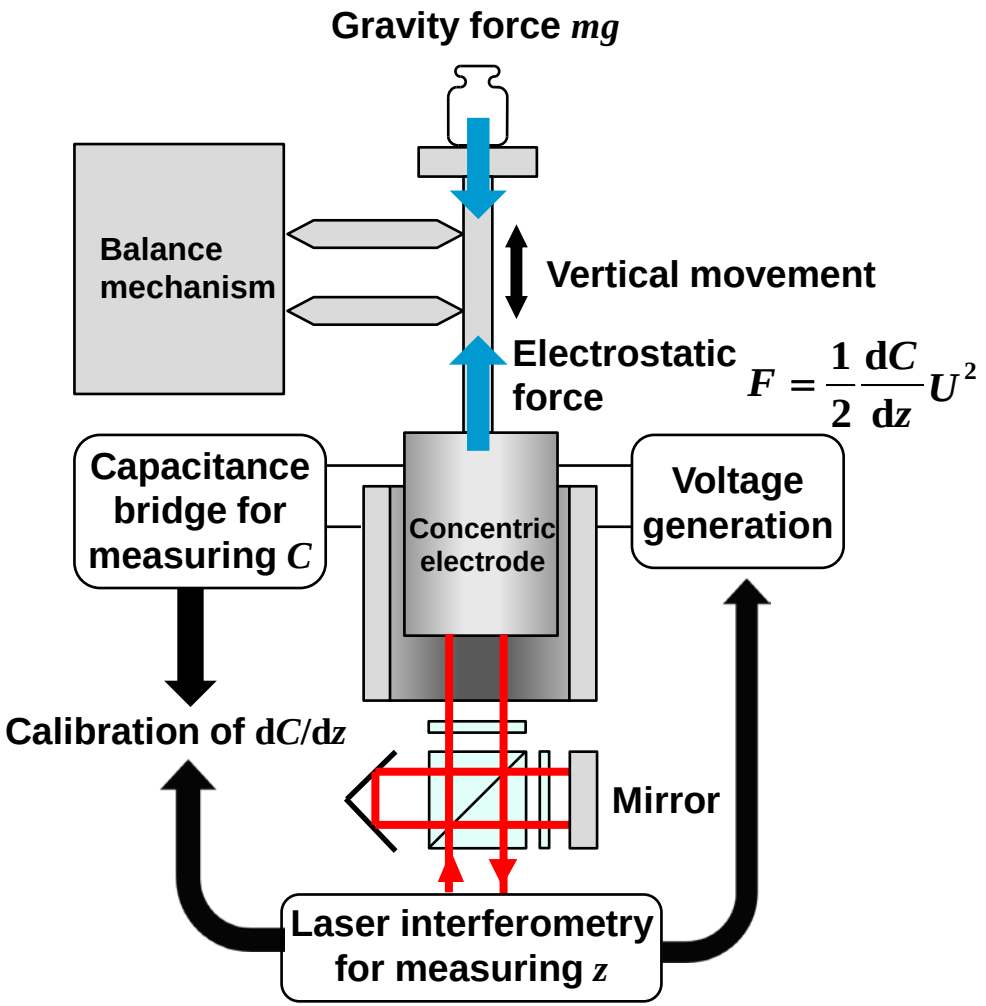
Electrical resistance: quantum Hall effect (h/e^2)

It is possible to determine the very small mass, force and torque from electrical measurements.

- Calibration of dC/dz
- Measurement of gravity force mg

$$mg = F = \frac{1}{2}\frac{dC}{dz}U^2$$

- Small mass standard realized without using weights



Voltage balance

Electrostatic force balance developed at NIST

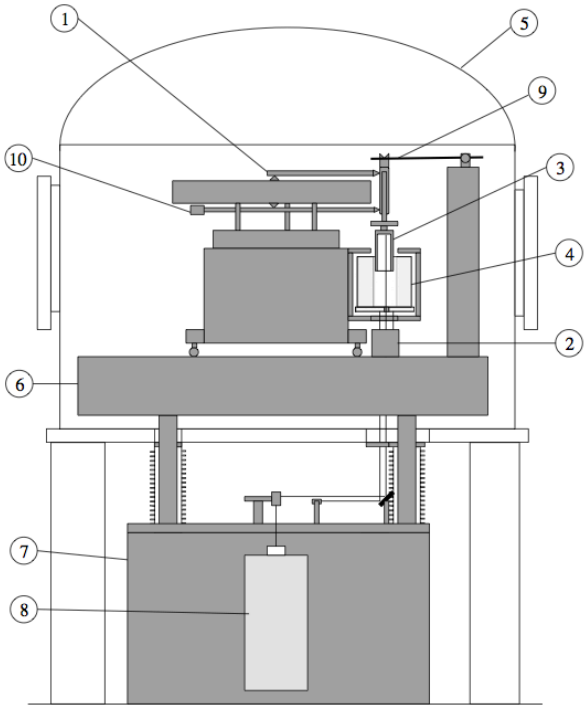
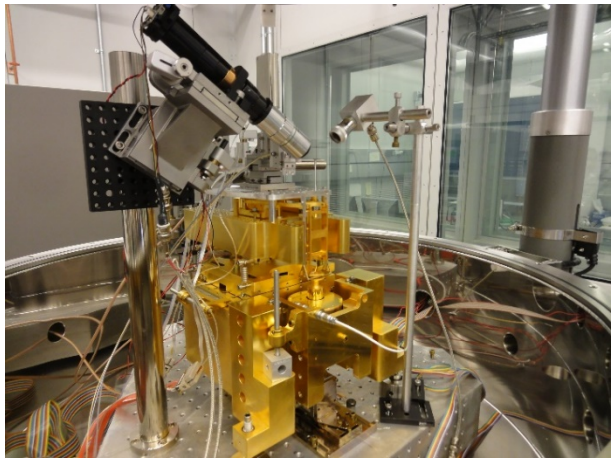
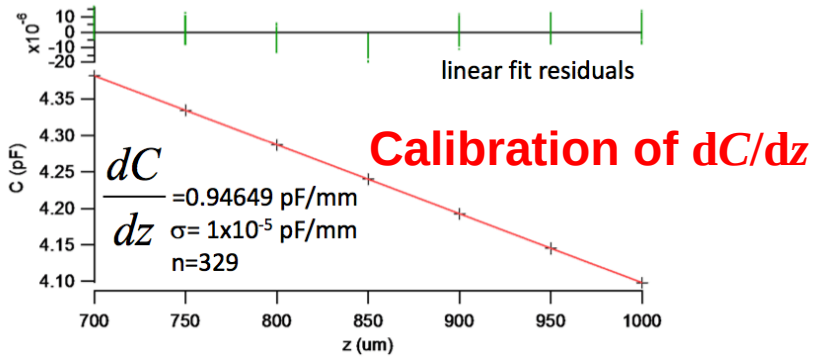


Figure 3. Schematic of balance components: (1) parallelogram balance, (2) differential plane mirror interferometer, (3) main inner electrode (cross-section), (4) main outer electrode (cross-section), (5) vacuum chamber, (6) optical table, (7) granite foundation block, (8) heterodyne laser light source, (9) mass lift and (10) counterweight.

Jon R Pratt, John A Kramar, David B Newell and Douglas T Smith: *Meas. Sci. Technol.*, 16 (2005) 2129-2137

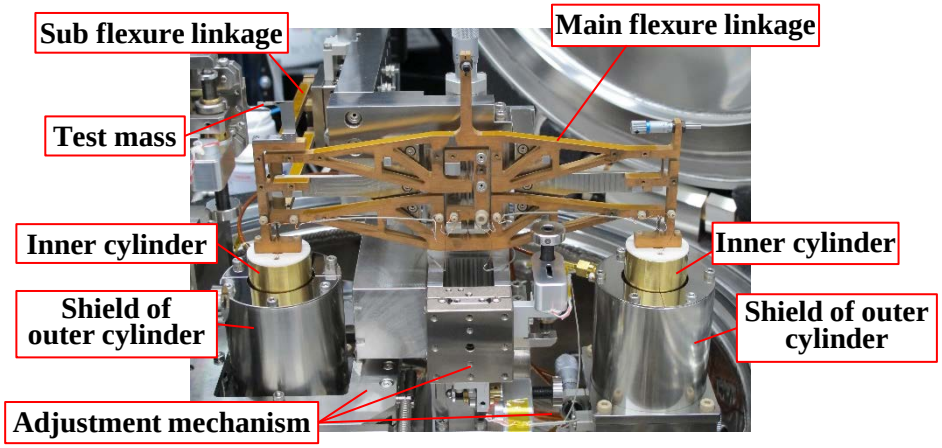




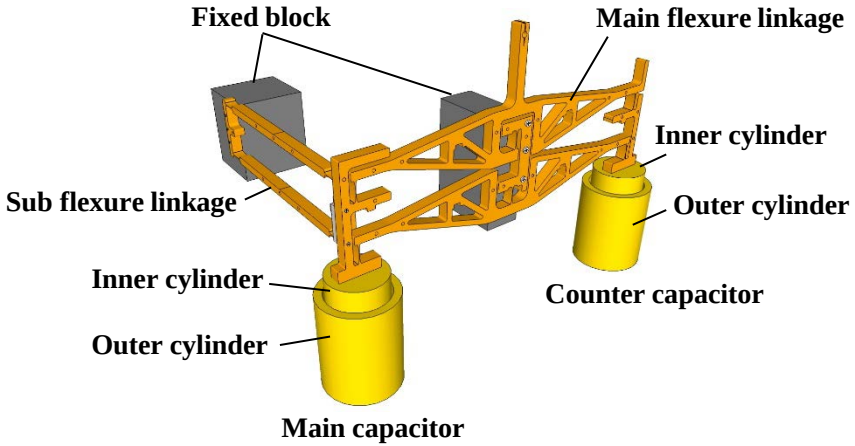
G. Shaw, J. Stirling, J. Kramar, A. Moses, P. Abbott, R. Steiner, A. Koffman, J. Pratt, Z. Kubarych: Milligram mass metrology using an electrostatic force balance, *Metrologia* 53, A86-A94 (2016)

Voltage balance with MEMS technologies

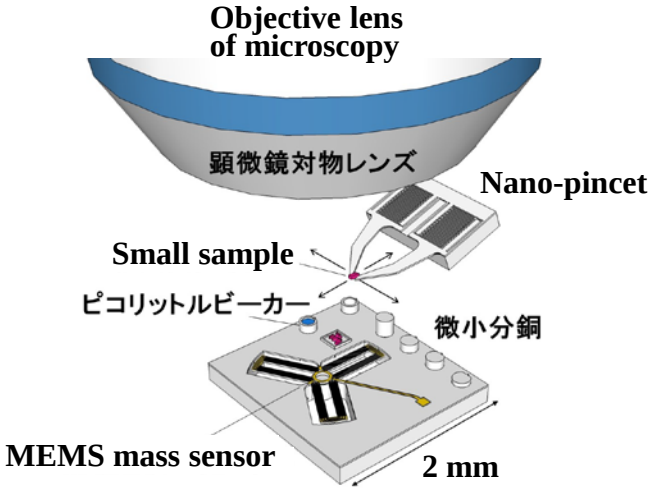
Nanogram region

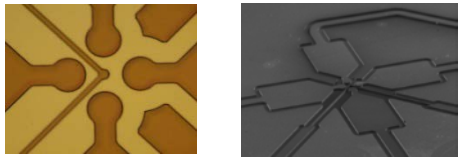


Monolithic Roberval mechanism realized by flexure hinges



Picogram region





Photoregist SEM image

MEMS sensor

Small mass measurement under microscope using MEMS technologies

Y. Yamamoto, K. Fujita and K. Fujii: SI Traceable Small Mass Measurement Using the Voltage Balance Apparatus at NMIJ, CPEM 2018, July 8-13, 2018, Paris

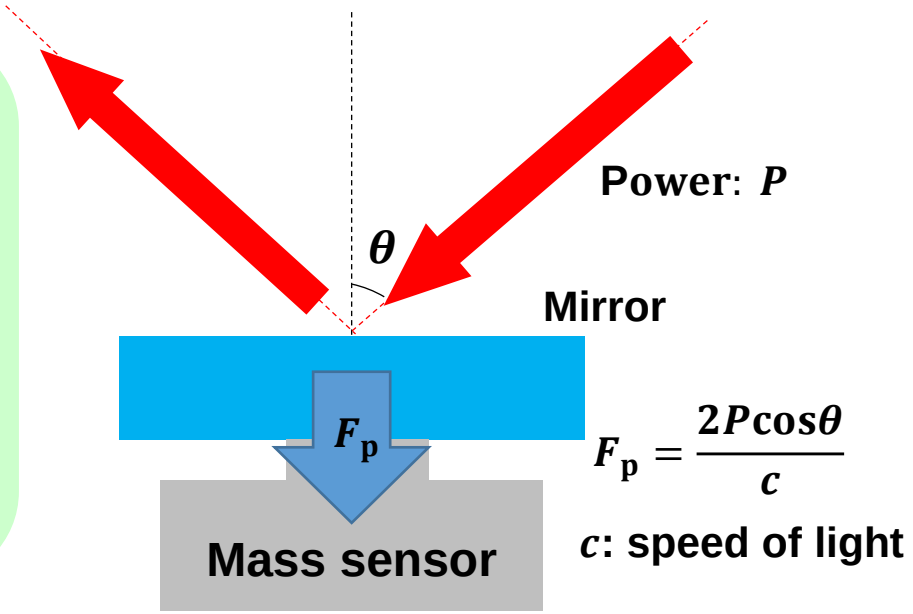
Optical radiation pressure for small force measurement

Principle

Reflection of optical power P

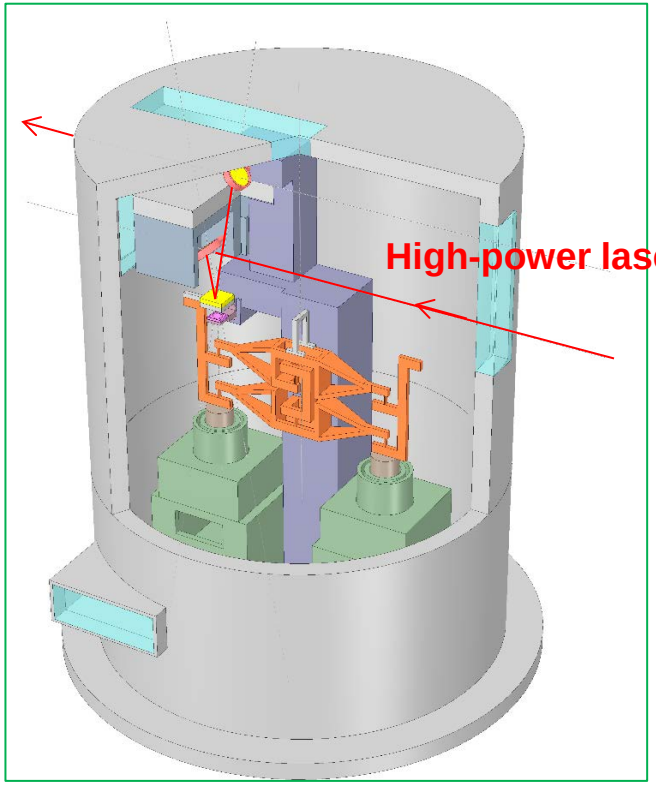
$$\text{Force: } F_p = \frac{2P\cos\theta}{c}$$

$$P = 1\ \text{W}, \theta = 0° \text{ (vertical incidence)}$$
$$F_p = 6.7\ \text{nN} \rightarrow m_p = 0.66\ \mu\text{g}$$



- Mass standard realized by optical power
- Optical power standard realized by the voltage balance based on the Planck constant
- Example: power monitoring for laser welding, extremely small mass measurement

Measuring the small mass and force using optical radiation pressure



High-power laser

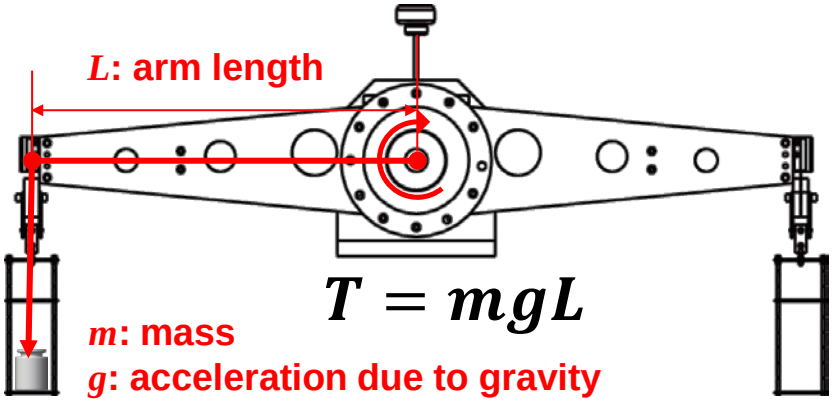
Mirror

Voltage balance

K. Fujita, Y. Yamamoto and K. Fujii: Radiation Pressure Measurement for Small Mass and Force Standard Using Voltage Balance Apparatus Developed at NMIJ, CPEM 2018, July 8-13, 2018, Paris

Small torque standard realization by electromagnetic force

Conventional method



$$T = mgL$$

New method

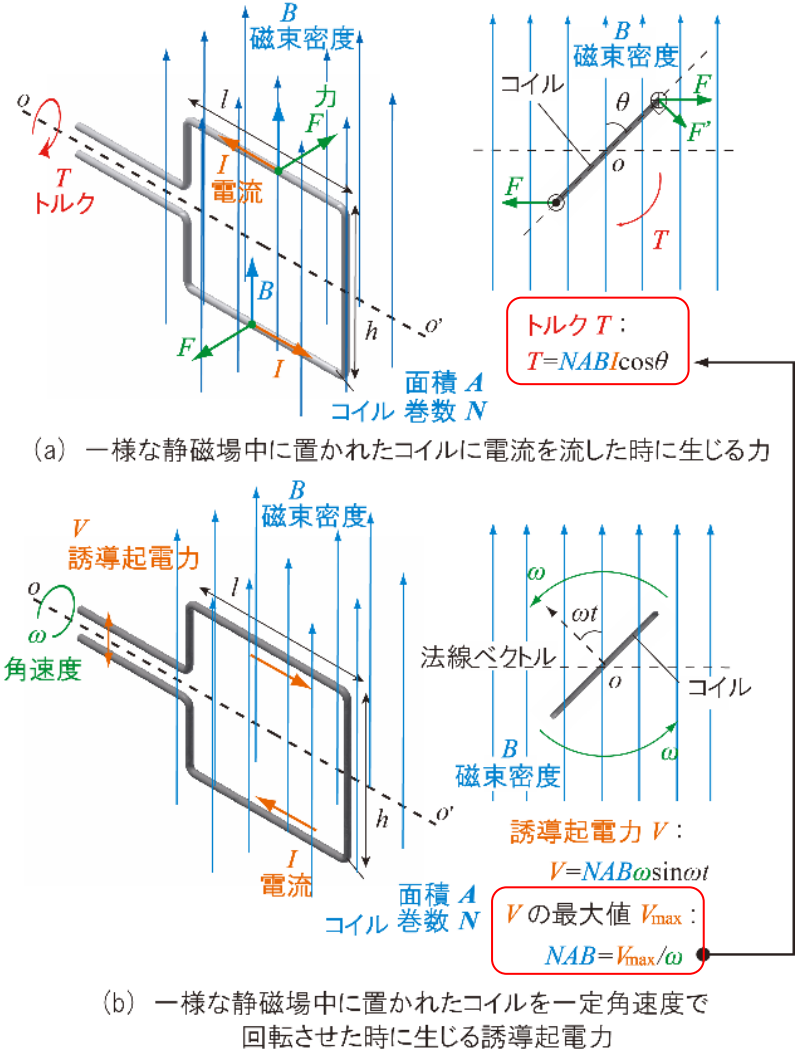
➢ Voltage measurement mode

Rotating a coil under with an angular velocity ω under magnetic flux B to generate voltage V

➢ Current measurement mode

When the current I is supplied to the coil, the mechanical power $T\omega$ is exactly equal to the electrical poser VI.

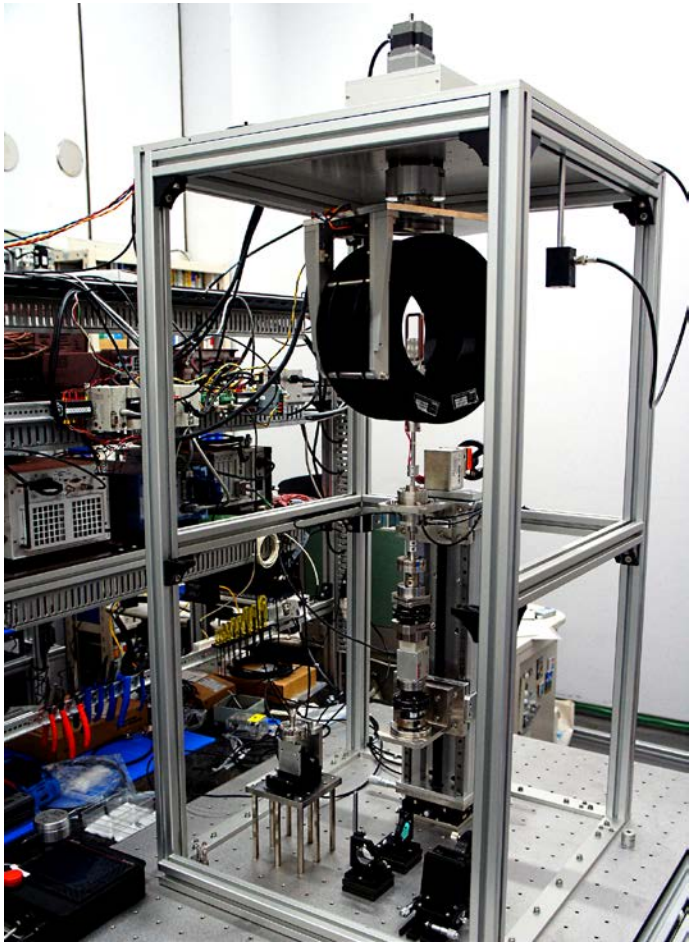
$$T\omega = VI$$



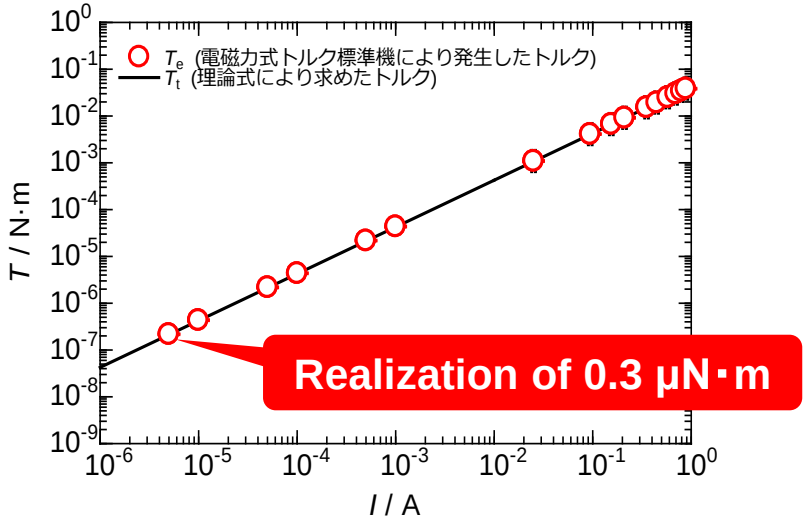
(a) 一様な静磁場中に置かれたコイルに電流を流した時に生じる力

(b) 一様な静磁場中に置かれたコイルを一定角速度で回転させた時に生じる誘導起電力

Development of small torque standard machine using the electromagnetic force



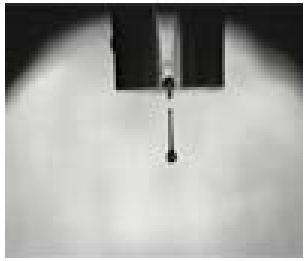
Relationship between the current and torque



Atsuhiro Nishino, Kazunaga Ueda and Kenichi Fujii: Design of a new torque standard machine based on a torque generation method using electromagnetic force, *Meas. Sci. Technol.*, 28 (2017) 025005 (11pp)

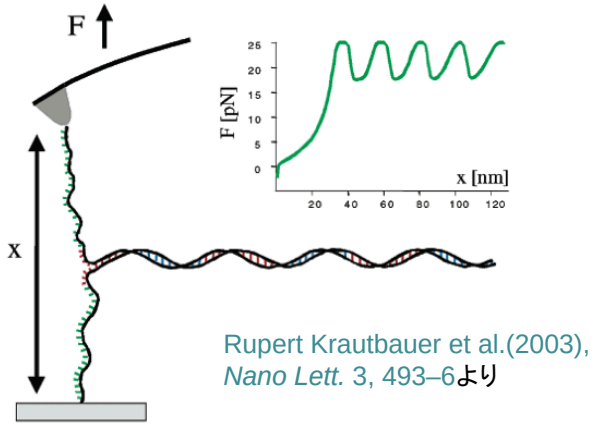
Redefinition of the kilogram paves a new way for industry

Creation of new medicines



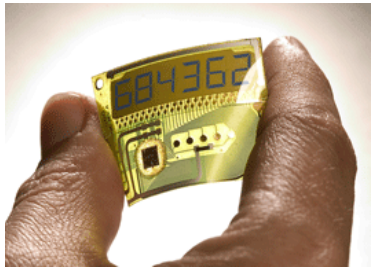
http://www.microjet.co.jp/index.html

Inkjet technologies
(mass control, evaluation of uniformities)



Rupert Krautbauer et al.(2003),
Nano Lett. 3, 493–6より

Micro force measurement
for bio molecules

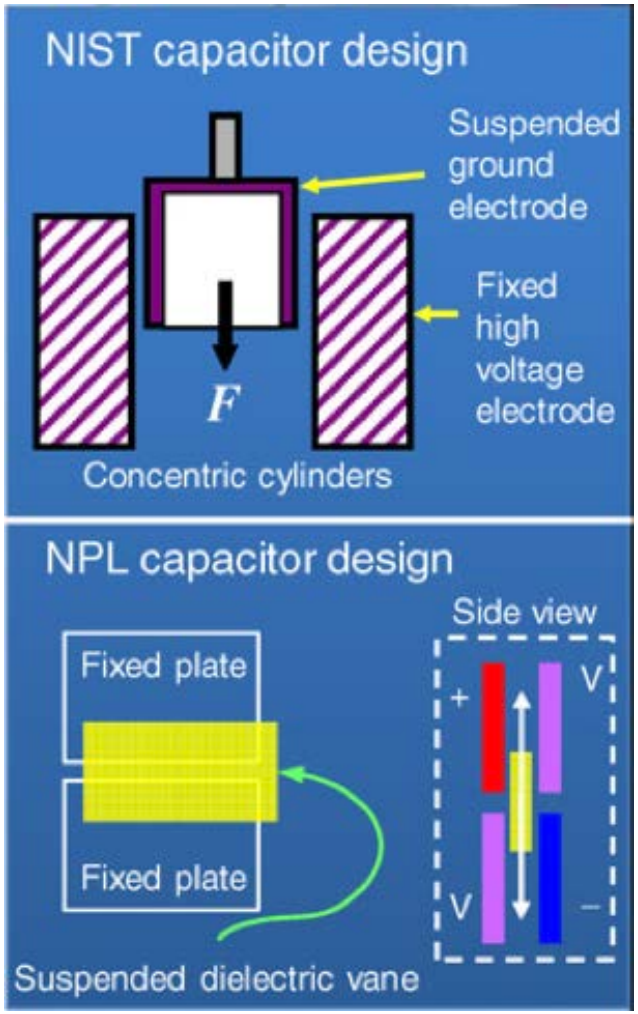


http://secureidnews.com/news-item/on-card-displays-become-reality-making-cards-more-secure/

https://business.Toshiba-memory.com/ja-jp/product/memory/bics.html

Thin film evaluation

Principle of the voltage balance



Metrologia, 49 (2012) 72

Force generation by capacitors

NIST : Electrostatic Force Balance (EFB)

Consists of two coaxial, conductive cylinder.

Inner one is electrically grounded, while outer one is applied a voltage and geometrically fixed.

NPL : Low Force Balance (LFB)

Consists of four fixed conductive plates and a moving dielectric vane.

$$F = \frac{1}{2}\frac{\mathrm{d}C}{\mathrm{d}z}U^2$$

***F*: generated force, *U*: applied voltage,**

***C*: capacitance, *z*: displacement from null position**