National Institute of Standards and Technology
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A torsion balance experiment with magnetic feedback

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NIST Big G workshop
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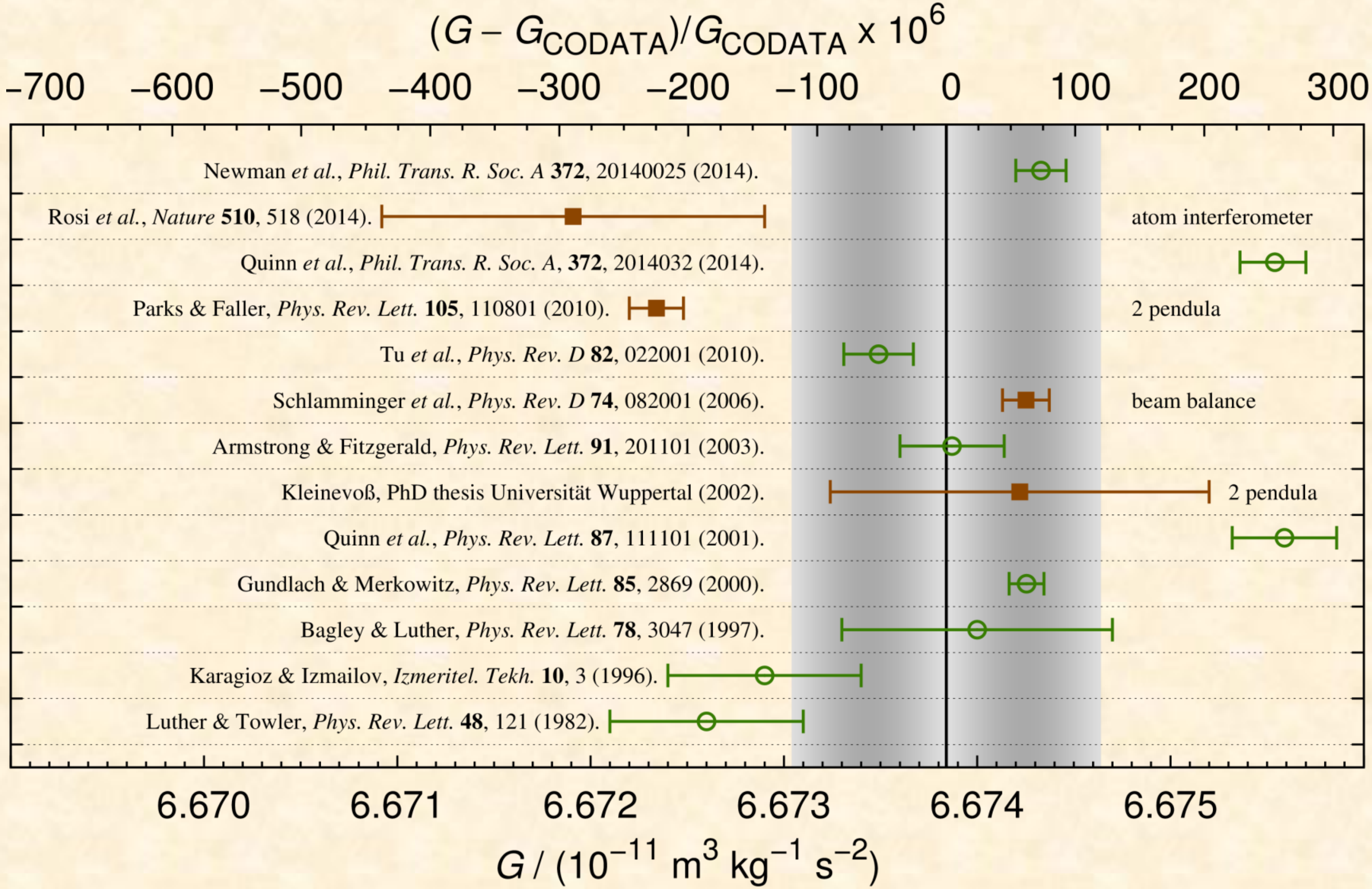
Starting point

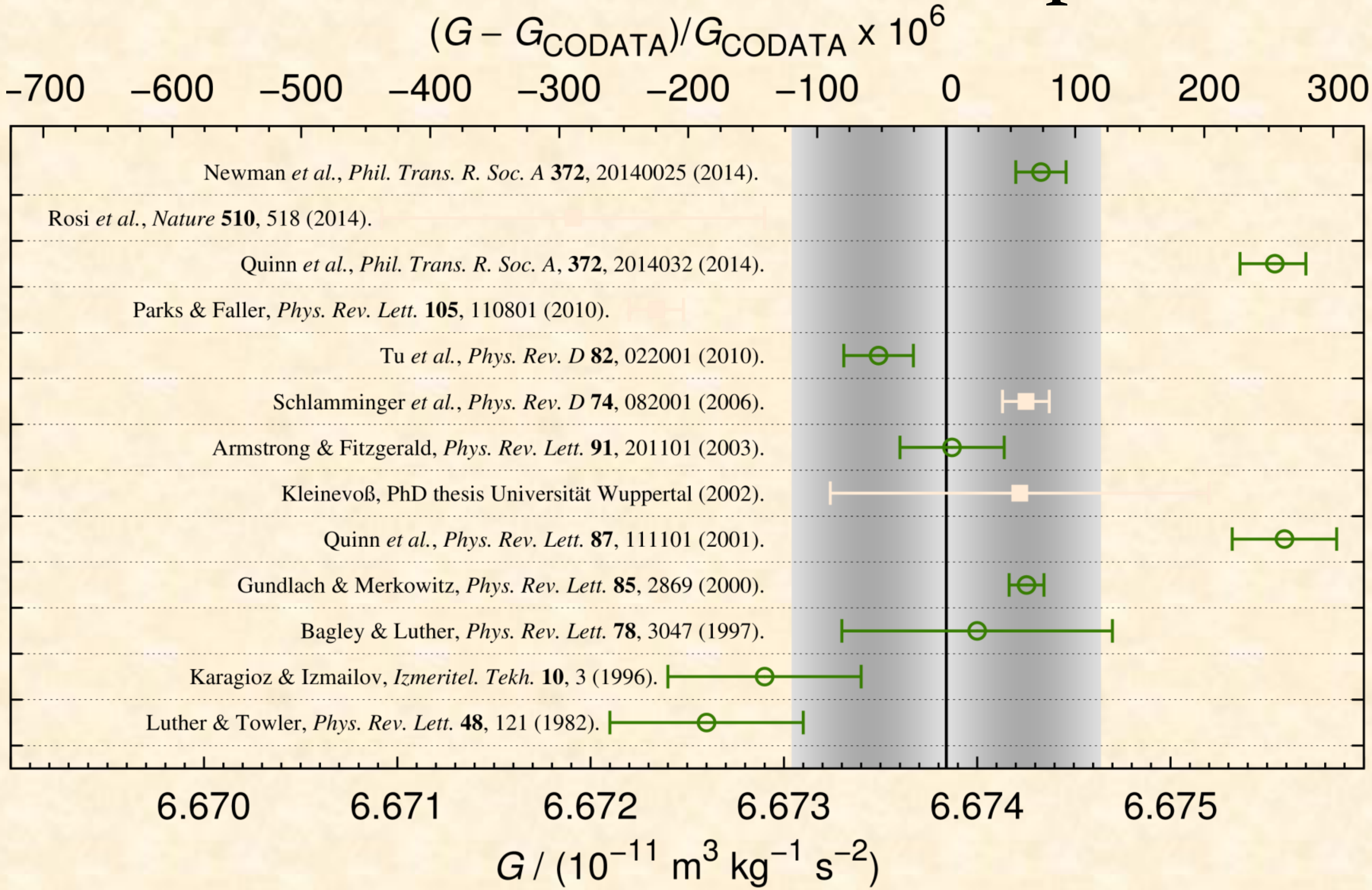
- Assume NIST takes the role to be a “Hub” for the G-Consortium.
- We would build two torsion balances that can be shipped around to external members of the consortium.

- Why torsion balances:
  - TBs contribute to the bulk of the discrepant data. Understand them better will help.
  - Is a practical device to measure weak forces.
  - Physics is simple => Possibility to get many collaborators.
  - Devices can be made compact and produced cheaply.
  - Remote support will be easier.
- Why two:
  - Adds additional robustness to the consortium.
  - Answers to questions like “Does one lab get consistent numbers with both instruments?” will provide additional information.

The current situation

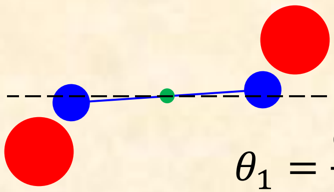


Emphasis on TB experiments

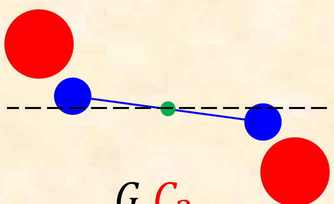


4 ways to use torsion balances

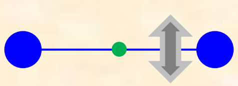
Static deflection



$$\theta_1 = \frac{G\,C_1}{\kappa}$$



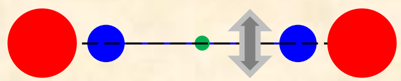
$$\theta_2 = \frac{G\,C_2}{\kappa}$$



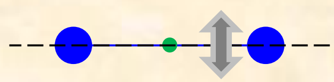
$$\kappa = I\omega^2$$

$$G = \frac{(\theta_1 - \theta_2)\omega^2}{C_1 - C_2} I$$

Time of swing



$$\omega_n{}^2 = \frac{\kappa + \kappa_n}{I}$$

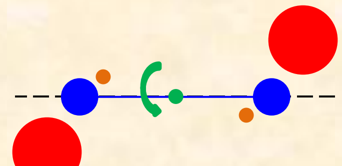


$$\omega_f{}^2 = \frac{\kappa + \kappa_f}{I}$$

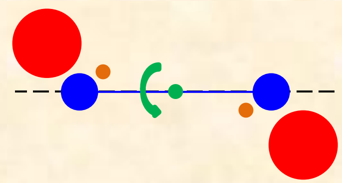
$$\kappa_n = G\,C_n \qquad \kappa_f = G\,C_f$$

$$G = \frac{\omega_n{}^2 - \omega_f{}^2}{(C_n - C_f)} I$$

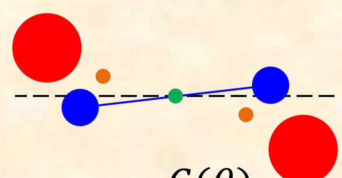
Electrostatic servo



$$G\,C_1 + \kappa\theta = \frac{\mathrm{d}C}{\mathrm{d}\theta} V_1{}^2$$



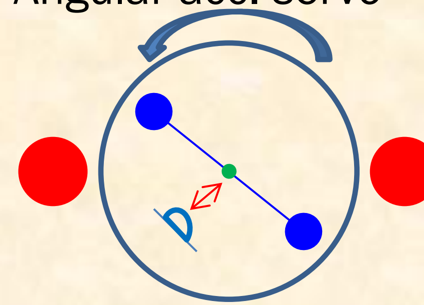
$$G\,C_2 + \kappa\theta = \frac{\mathrm{d}C}{\mathrm{d}\theta} V_2{}^2$$



$$C(\theta)$$

$$G = \frac{\mathrm{d}C}{\mathrm{d}\theta} \frac{(V_1{}^2 - V_2{}^2)}{C_1 - C_2}$$

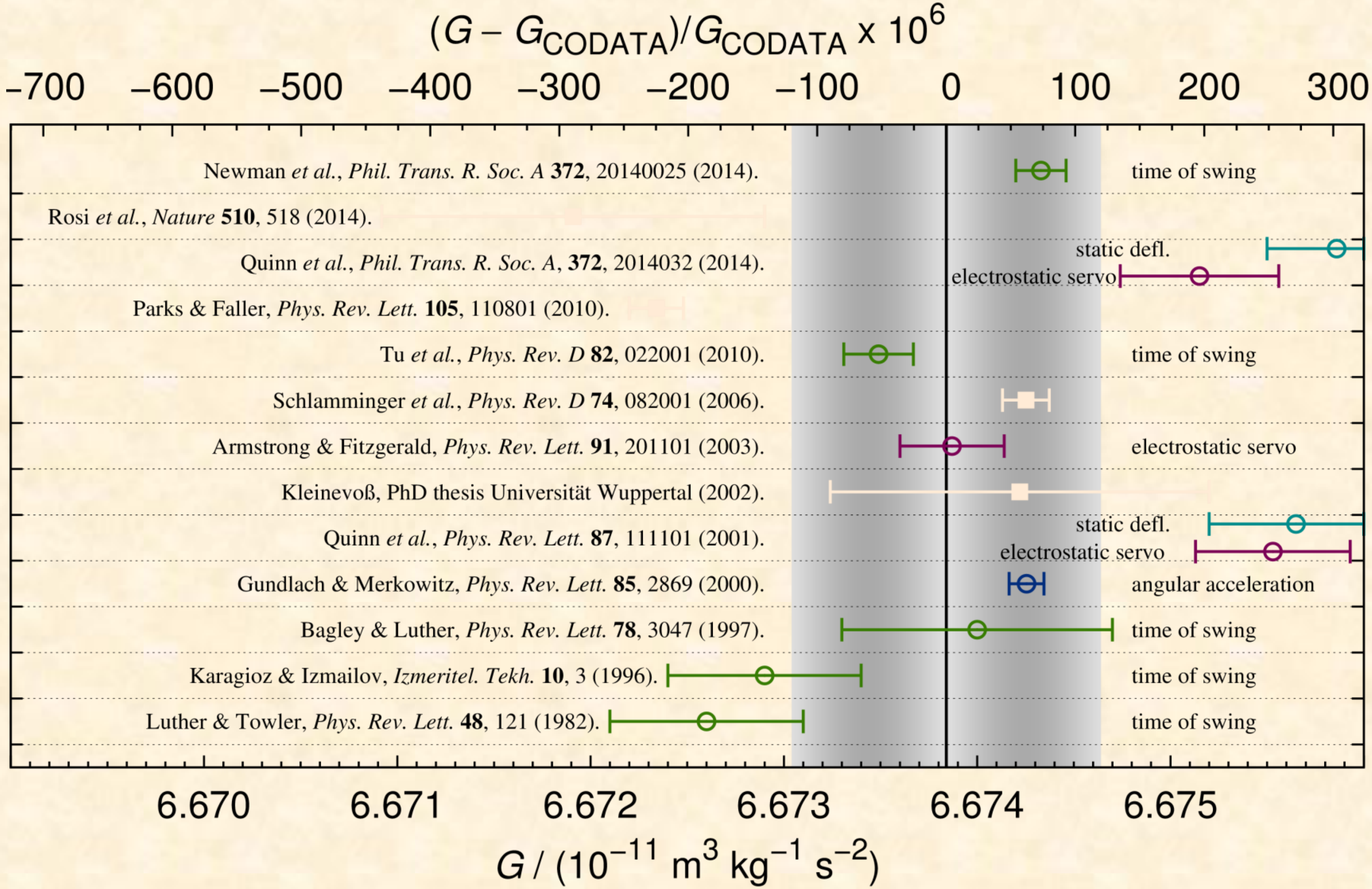
Angular acc. servo



$$\ddot{\theta} = \frac{16\pi}{5} G \frac{q_{22}Q_{22}}{I} \sin 2\theta$$

$$G = \frac{5}{16\pi} \frac{I}{q_{22}Q_{22}} \ddot{\theta}_0$$

4 TB methods


(G – G_CODATA)/G_CODATA x 10^6
–700 –600 –500 –400 –300 –200 –100 0 100 200 300
Newman et al., Phil. Trans. R. Soc. A 372, 20140025 (2014).
time of swing
Rosi et al., Nature 510, 518 (2014).
Quinn et al., Phil. Trans. R. Soc. A, 372, 2014032 (2014).
static defl.
electrostatic servo
Parks & Faller, Phys. Rev. Lett. 105, 110801 (2010).
Tu et al., Phys. Rev. D 82, 022001 (2010).
time of swing
Schlamminger et al., Phys. Rev. D 74, 082001 (2006).
Armstrong & Fitzgerald, Phys. Rev. Lett. 91, 201101 (2003).
electrostatic servo
Kleinevoß, PhD thesis Universität Wuppertal (2002).
Quinn et al., Phys. Rev. Lett. 87, 111101 (2001).
static defl.
electrostatic servo
Gundlach & Merkowitz, Phys. Rev. Lett. 85, 2869 (2000).
angular acceleration
Bagley & Luther, Phys. Rev. Lett. 78, 3047 (1997).
time of swing
Karagioz & Izmailov, Izmeritel. Tekh. 10, 3 (1996).
time of swing
Luther & Towler, Phys. Rev. Lett. 48, 121 (1982).
time of swing
6.670 6.671 6.672 6.673 6.674 6.675
G / (10^-11 m^3 kg^-1 s^-2)

From the data

- Static deflection
  - seems difficult
- Time of swing
  - Recently 5 measurements.
  - Seems to measure low.
  - Applying the Kuroda correction moves the measured values even lower!
- Electrostatic feedback
  - Susceptible to errors measuring the capacitance gradient.
  - Contact potentials and surface potentials can introduce biases.
- Angular acceleration
  - Elegant method.
  - Only one data point.
  - We do not know how reproducible this method is.

Based on these observations..

…I propose to build

Jens Gundlach's Apparatus

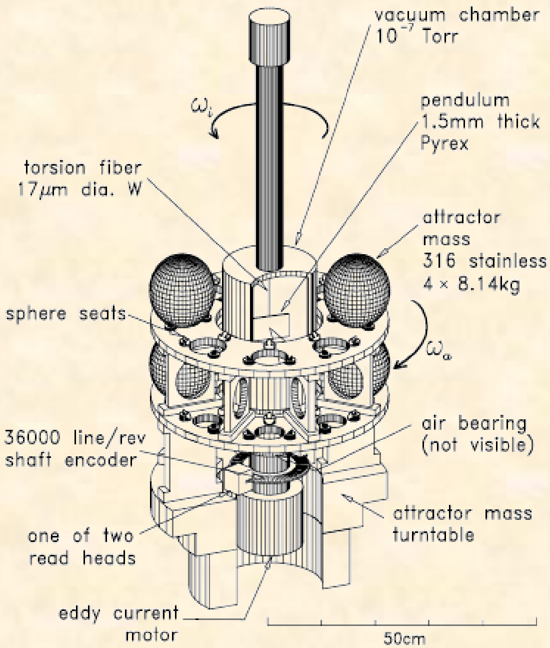


FIG. 1. Cut-away view of the apparatus.

?

- A torsion balance with servo.
- But not an electrostatic servo.

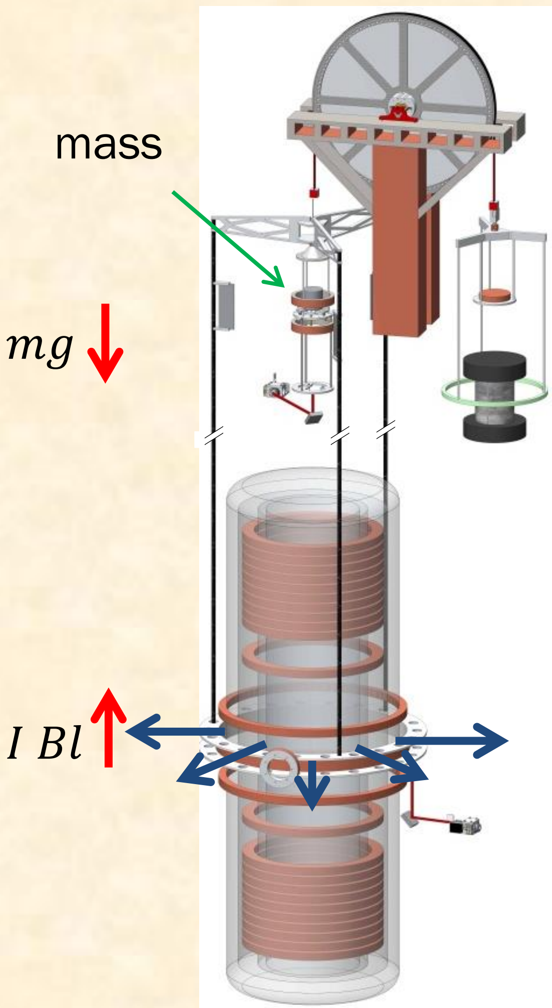
Watt balance primer

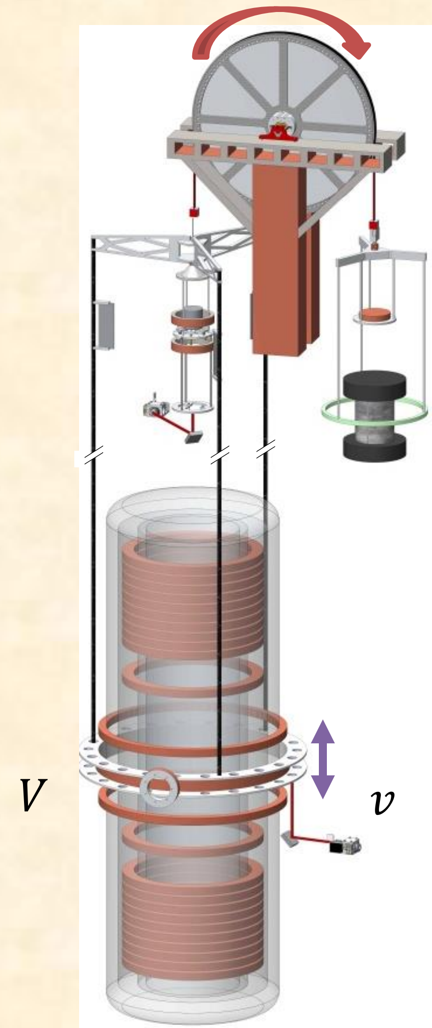
Force mode

$$mg = I\,Bl$$

$$V = v\,Bl$$

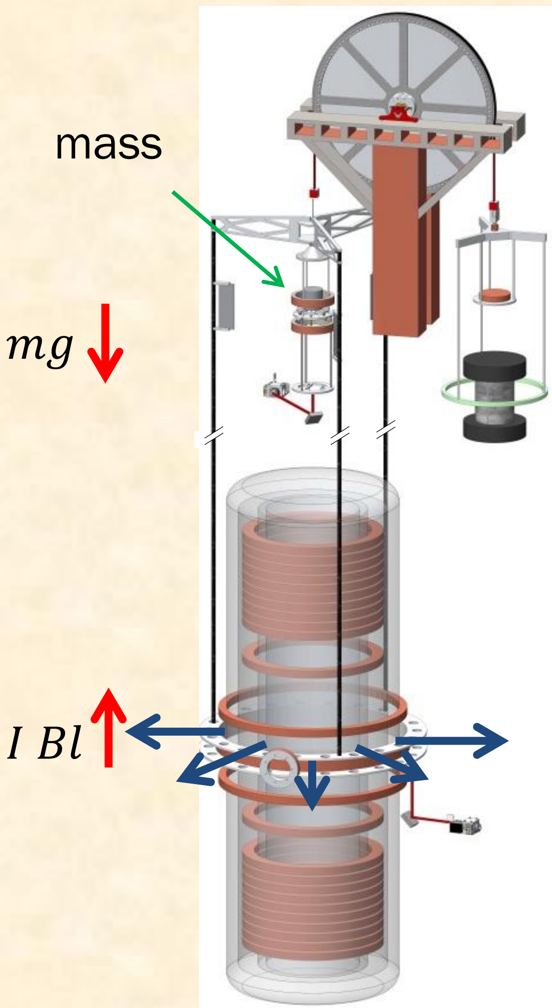
Velocity mode





Watt balance primer

Force mode



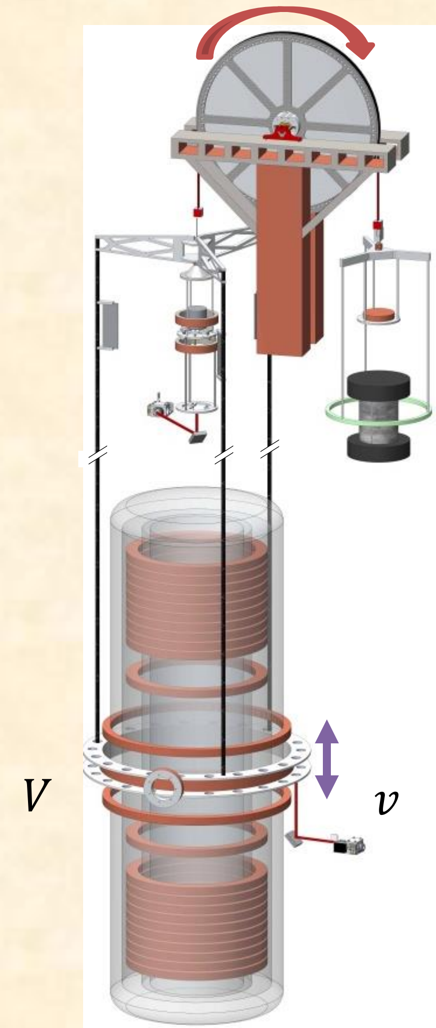
$$mg = I\,Bl$$

$$V = v\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

$$mgv = VI$$

Velocity mode



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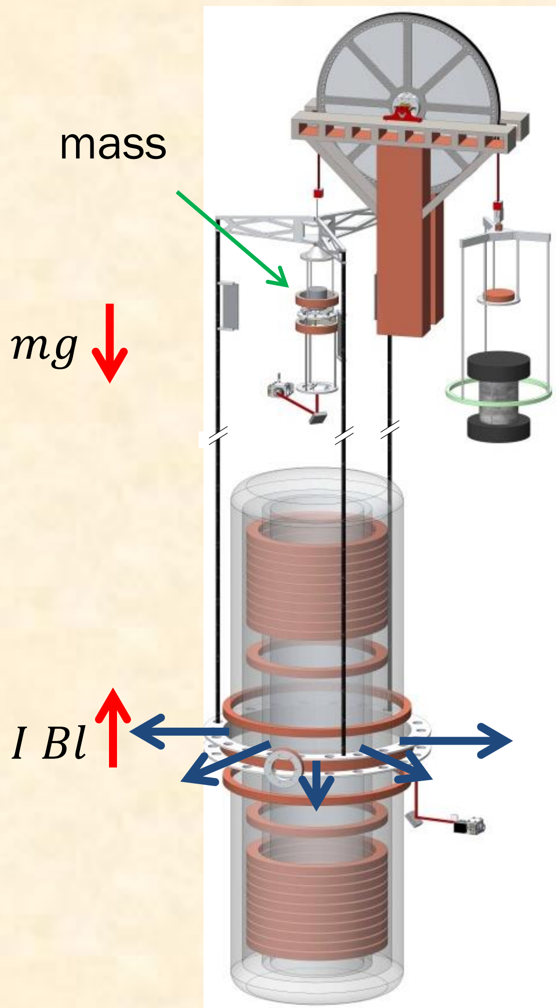
Watt balance primer

Force mode



$$mg = I\,Bl$$

$$V = v\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

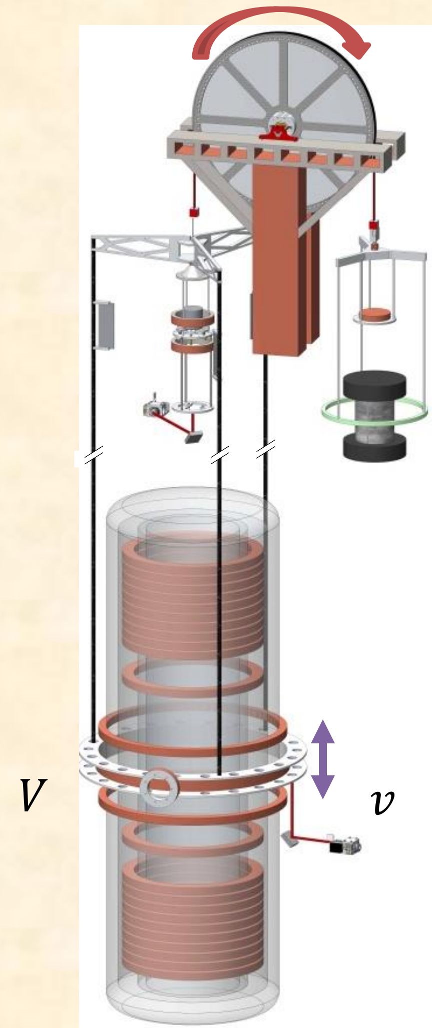
$$mgv = VI$$

B.P. Kibble and I.A. Robinson, "Principles of a new generation of simplified and accurate watt balances", *Metrologia* **51** S132 (2014).

If the motion can be described by one variable, most error terms cancel.

A torsion balance is a prime example of a 1 dimensional system.

Velocity mode



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Torsion Watt Balance (TWB)

$$F = I\,Bl$$

$$V = v\,Bl$$

$$VI = Fv$$

- Bl must remain constant between modes.

$$N = I\,Bl\,r$$

$$V = \omega\,Bl\,r$$

$$VI = N\omega$$

- Bl and r must remain constant between modes.

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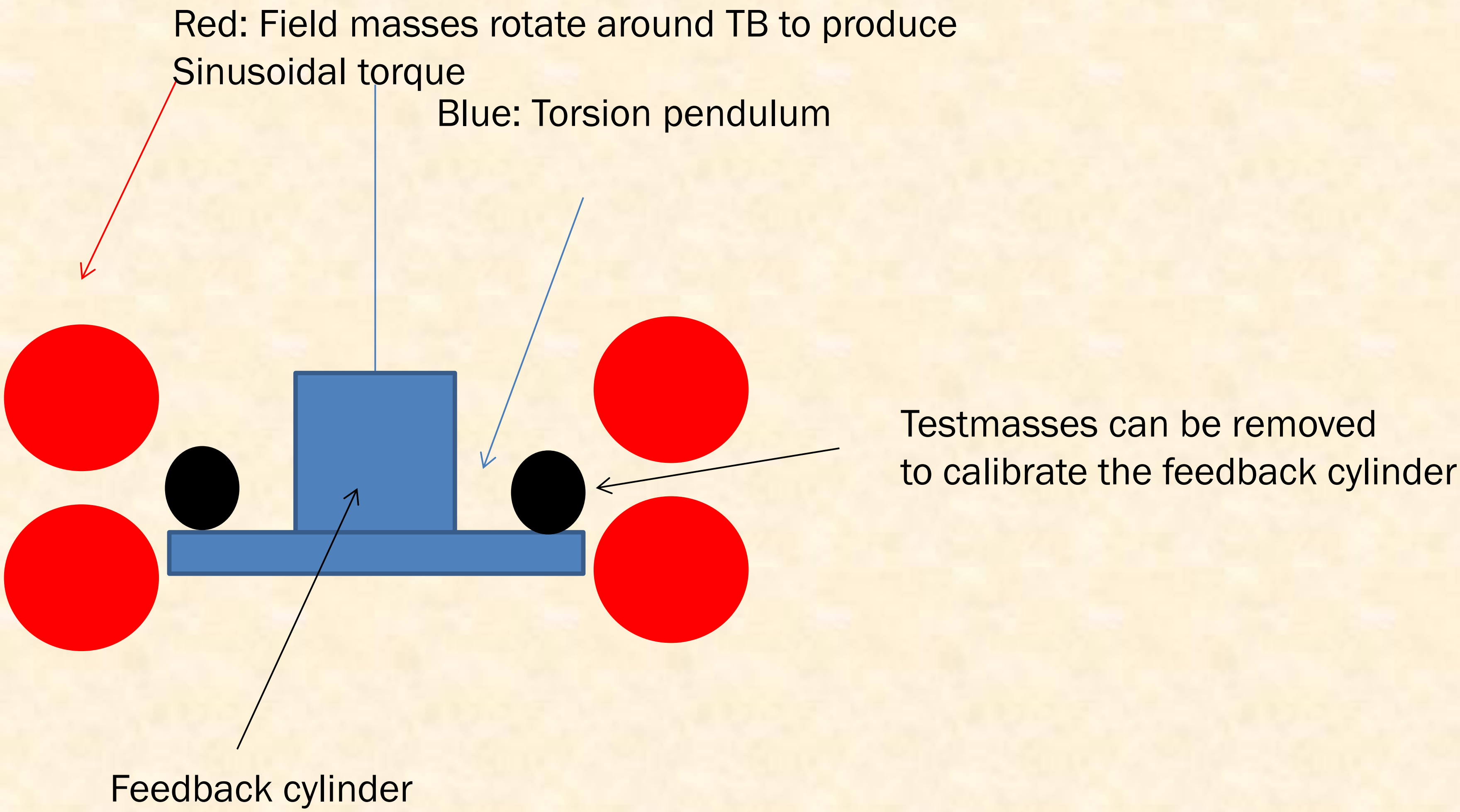
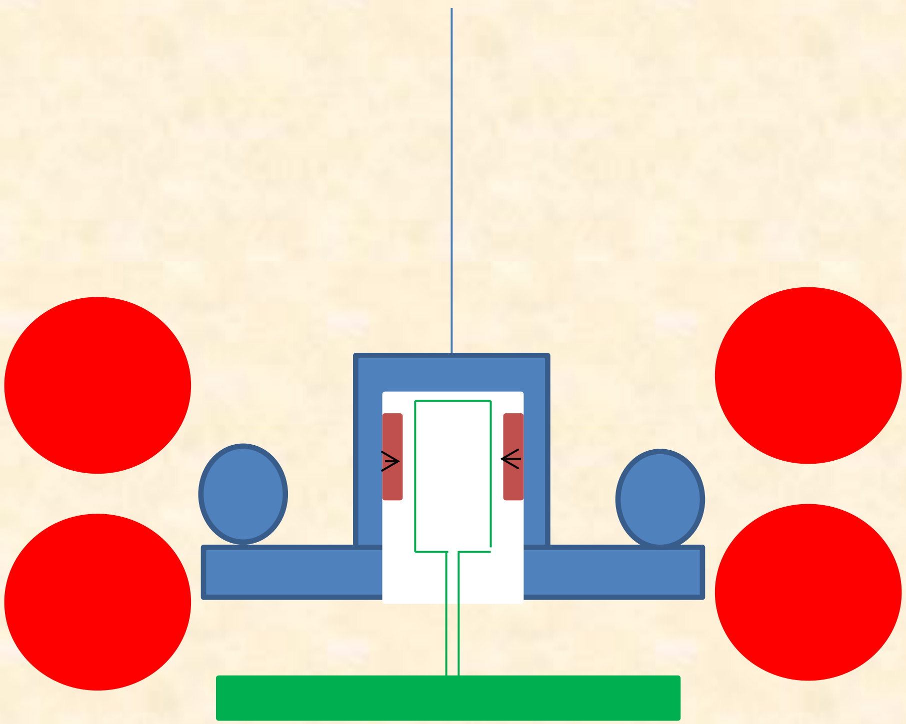
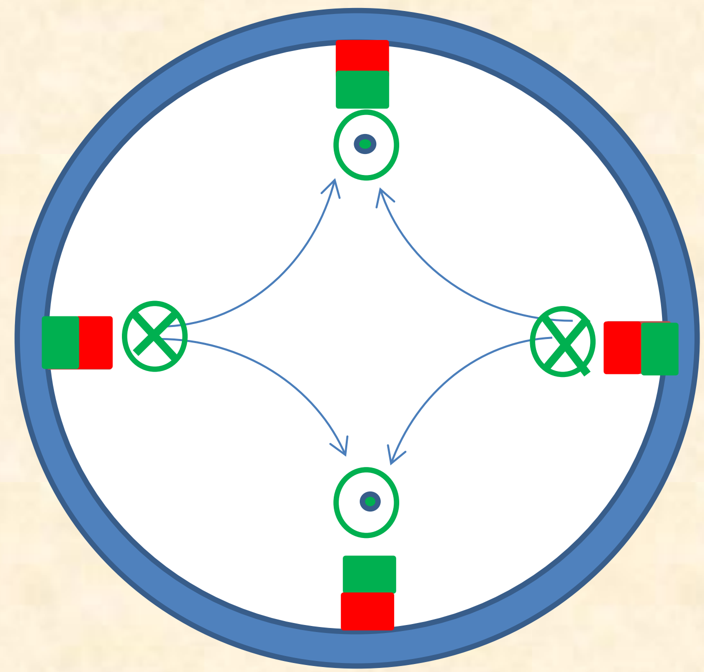
Principle Schematic



Let’s look inside the cylinder

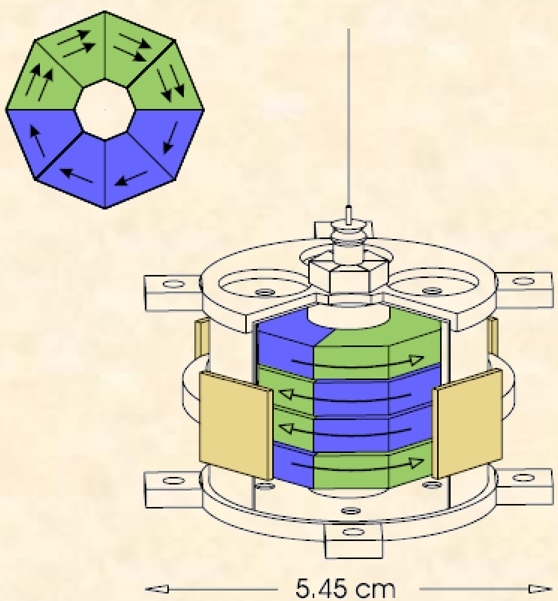


x,y,z tip/tilt stage



A magnet on a TB?

B.R. Heckel *et al.*,”Preferred-frame and CP-violation tests with polarized electrons” *PRD* **78** 092006 (2008).



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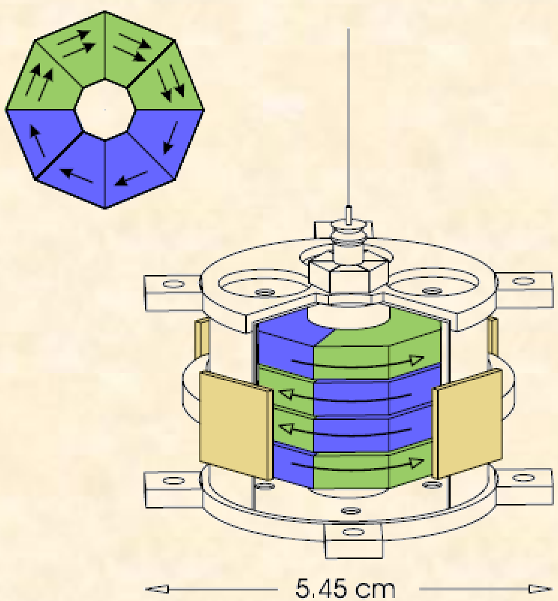

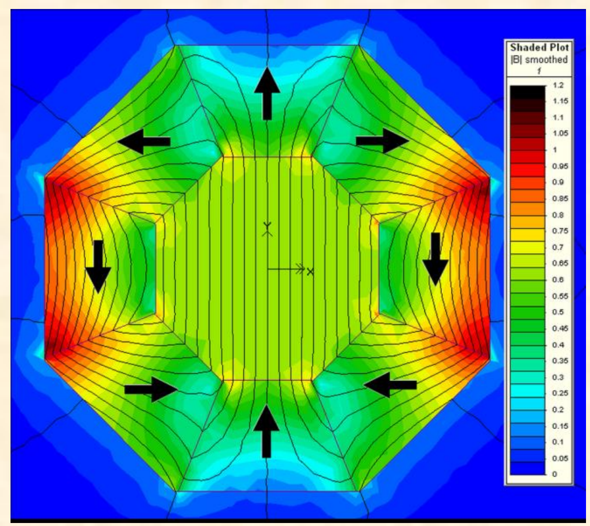

Source: Wikipedia,
Halbach array

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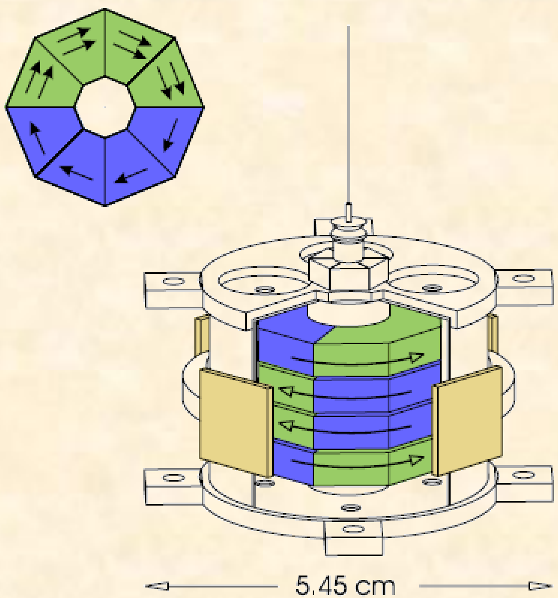
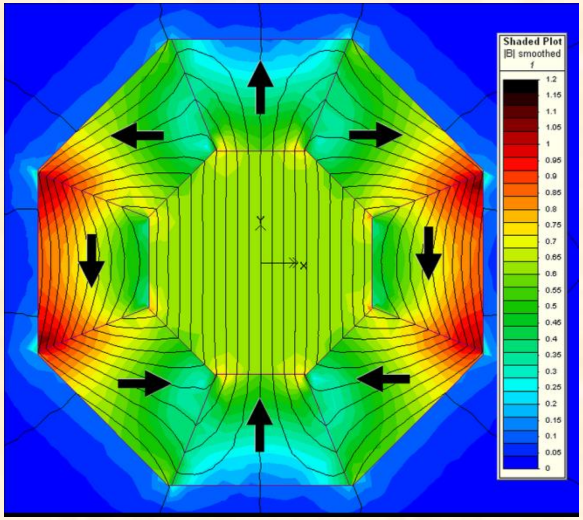
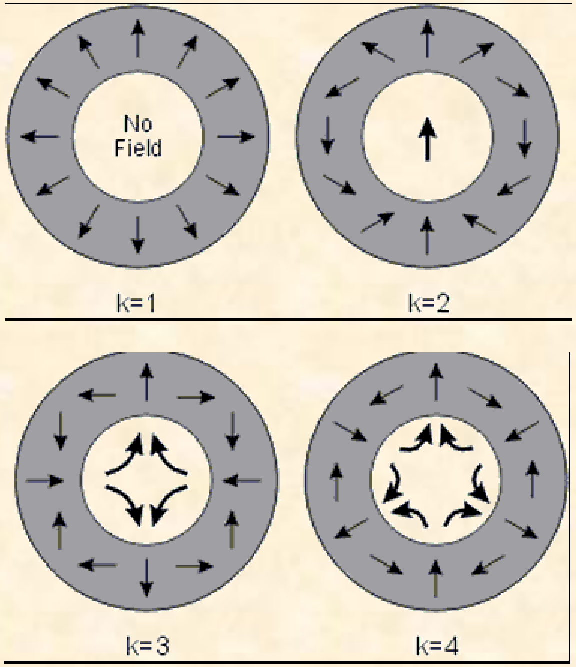






Source: Wikipedia, Halbach array

A few numbers

Typical torques in big G experiments: $3 \times 10^{-12}\ \mathrm{Nm} \leq N \leq 3\ \times 10^{-8}\ \mathrm{Nm}$

Reasonable magnetic flux densities: $B = 0.2\ \mathrm{T}$

Wire length: $\mathrm{l} = 8\ \mathrm{m}$

Lever arm: $\mathrm{r} = 2.5\ \mathrm{cm}$

Flux integral constant: $Blr = 0.04\ \mathrm{T\ m^2}$

Torque mode:

A current of $\mathrm{I} = 0.5\ \mu\mathrm{A}$

produces $\mathrm{N} = 2 \times\ 10^{-8}\ \mathrm{Nm}$

The current runs through $\mathrm{R} = 100\ \mathrm{k\Omega}$

to produce $V_R = 50\ \mathrm{mV}$

$$N = I\,Bl\,r = \frac{V_R}{R}\,Bl\,r$$

Angular velocity mode: $\omega = \varphi_o \frac{2\pi}{T}$

$$V = \omega\,Bl\,r$$

Where the angle $\varphi_0 = 4\pi$

Is the amplitude of the free oscillation

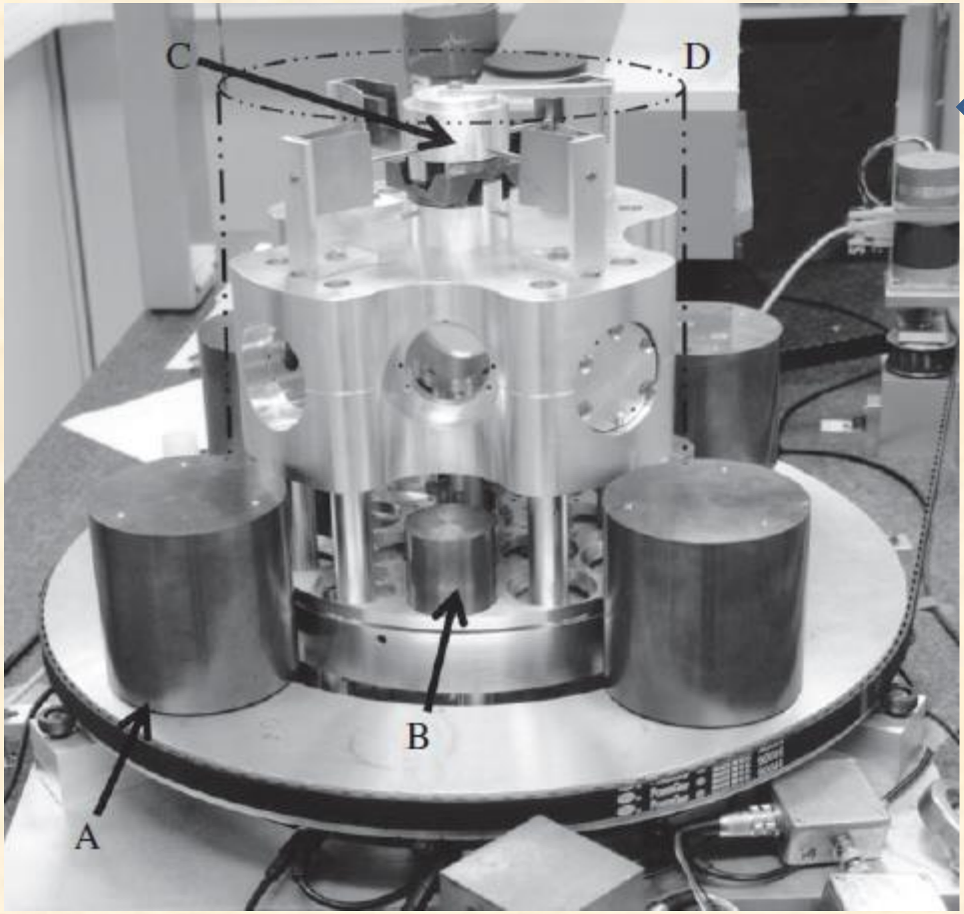
and $T = 60\ \mathrm{s}$

the period.

$$N = \frac{V_R}{R}\frac{V}{\omega}$$

With these numbers we get $V = 52.6\ \mathrm{mV}$

How could such an apparatus look like?



Terry Quinn's experiment

Not quite, torsion balance needs to be able to rotate by 360°.But this instrument will be similar in size.

Is this possible noise-wise?

In the fiber: $S_N{}^{0.5}(f) = \sqrt{\frac{4k_B T\kappa}{2\pi f Q}}$

Quinn et al.	$\kappa = 2 \times 10^{-4}$ Nm
here	$\kappa = 8 \times 10^{-4}$ Nm
hence	$S_N{}^{0.5}(f) = 1.2 \times 10^{-13}\ \mathrm{Nm}/\sqrt{\mathrm{Hz}}$
Signal:	$N \sim 3 \times 10^{-8}$ Nm
Relative in 1 s	$\sigma_N / N \sim 3 \times 10^{-6}$

✓

Is this possible noise-wise?

In the resistor: $S_V{}^{0.5}(f) = \sqrt{4k_B TR}$

here $R = 100\ \mathrm{k\Omega}$

$S_V{}^{0.5}(f) = 4 \times\ 10^{-8}\ \mathrm{V/\sqrt{Hz}}$

Signal: $V \sim 50\ \mathrm{mV}$

Relative in 1 s $\sigma_V/V \sim 8\ \times 10^{-7}$

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Summary

- NIST would be ideal to be one hub in the G-Consortium.
- We would build two instruments:
  - Angular acceleration servo in the manner of Jens Gundlach's.
  - Torsion watt balance.
- Both devices will be thoroughly in house.
- We will perform big G measurements with both torsion balances.
- Then the devices will be shipped to external consortium members.
- NIST will provide support to external collaborators if necessary.
- Projected timeline for the project: ~ 5 years.