Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of Justice and Police EJPD
Federal Office of Metrology METAS

The watt balance route towards a new definition of the kilogram

Blaise Jeanneret

Watt balance team

- BWM I

  Ali Eichenberger

  Henri Baumann, Beat Jeckelmann, Blaise Jeanneret

  Walter Beer (retired in 2002)

- BWM II

  H. Baumann, Z. Li,

  Ch. Béguin (Mettler-Toledo), D. Tommasini (CERN),
  R. Clavel, F. Cosandier (EPFL), N. Waldvogel (Uni ZH)

- METAS colleagues

  Electricity, optics, length and mass laboratories

  Electronic and mechanical shops

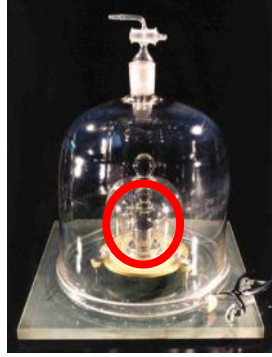
METAS

Outline

- The kilogram today
- Review of experimental strategies
- The watt balance approach
  - Principle
  - The different projects around the world
  - Details and results of the METAS watt balance BWM I
  - The new METAS project BWM II
- The Planck constant today & the new definition

METAS

Definition of the mass unit



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

- 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) + members of MC).

Weakness of the present definition:

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

METAS

The Swiss kg #38

Comité International des Poids & Mesures

CERTIFICAT

DU

BUREAU INTERNATIONAL DES POIDS ET MESURES

Les résultats combinés de ces 273 comparaisons complètes ou 1092 pesées individuelles ont donné, par le calcul de compensation de tout le système, pour le Kilogramme N.° 38 l'équation suivante:

PROTOTYPE N° 38 = 1 kg + 0 mg, 183 ± 0 mg, 002

BUREAU INTERNATIONAL
des Poids et Mesures,
(Pavillon de Breteuil, près Sèvres)
le 28 Septembre 1889.

Le Directeur du Bureau,

Dr. René Benoît

Certifié conforme:

Pour le Comité International des Poids et Mesures,

Le Secrétaire,

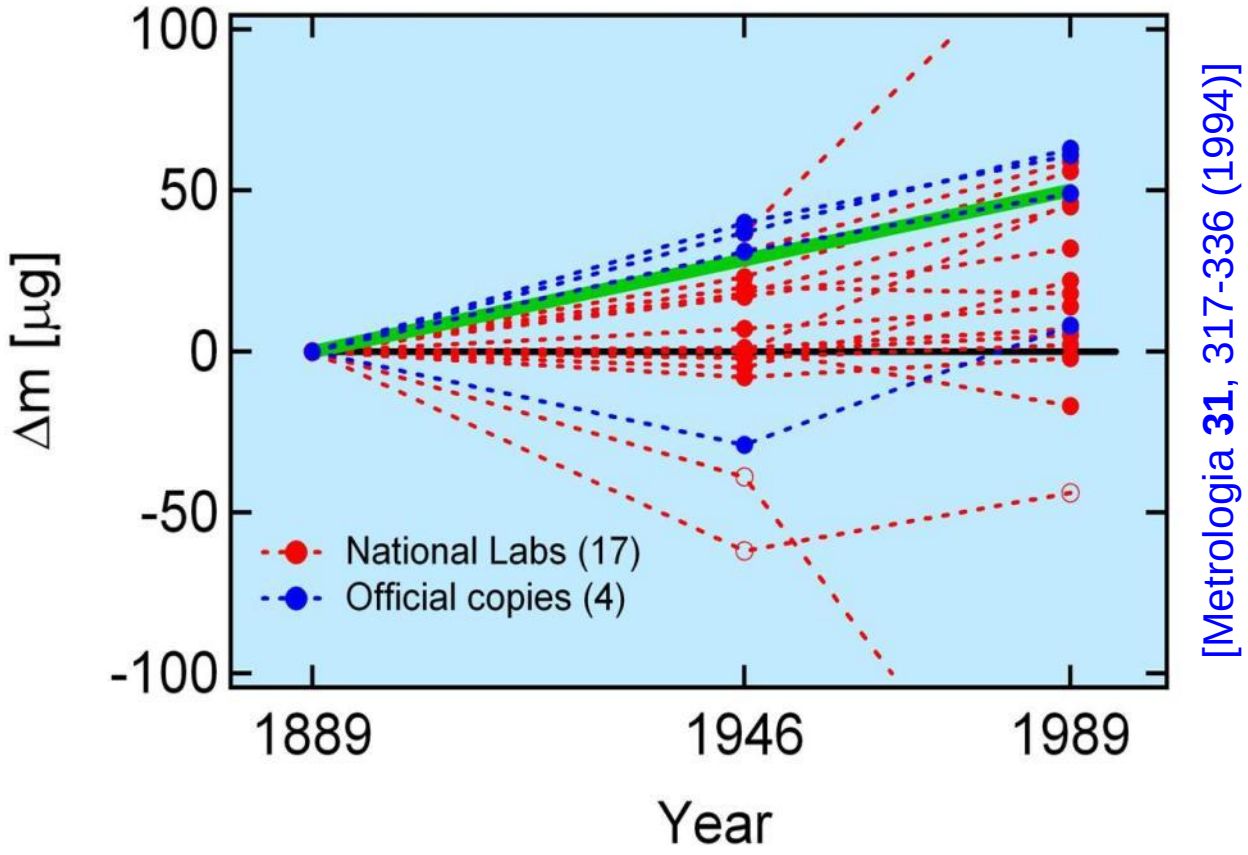
Dr. Ad. Hirsch

Le Président,

J. Cat Marquis de Melhaën

METAS

Results of the 3rd Periodic Verification of National Prototypes of the kg

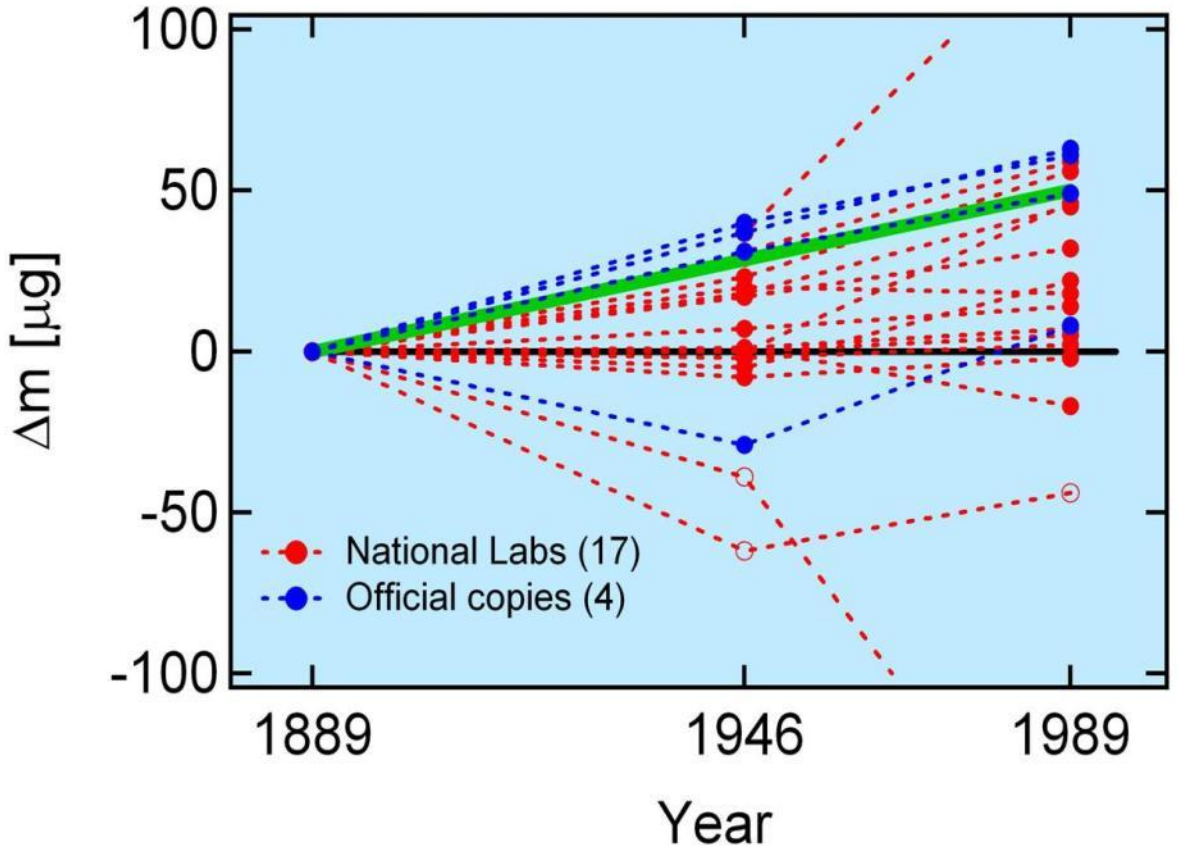


[Metrologia **31**, 317-336 (1994)]

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

~ 50 μg / 100 years

Results of the 3rd Periodic Verification of National Prototypes of the kg

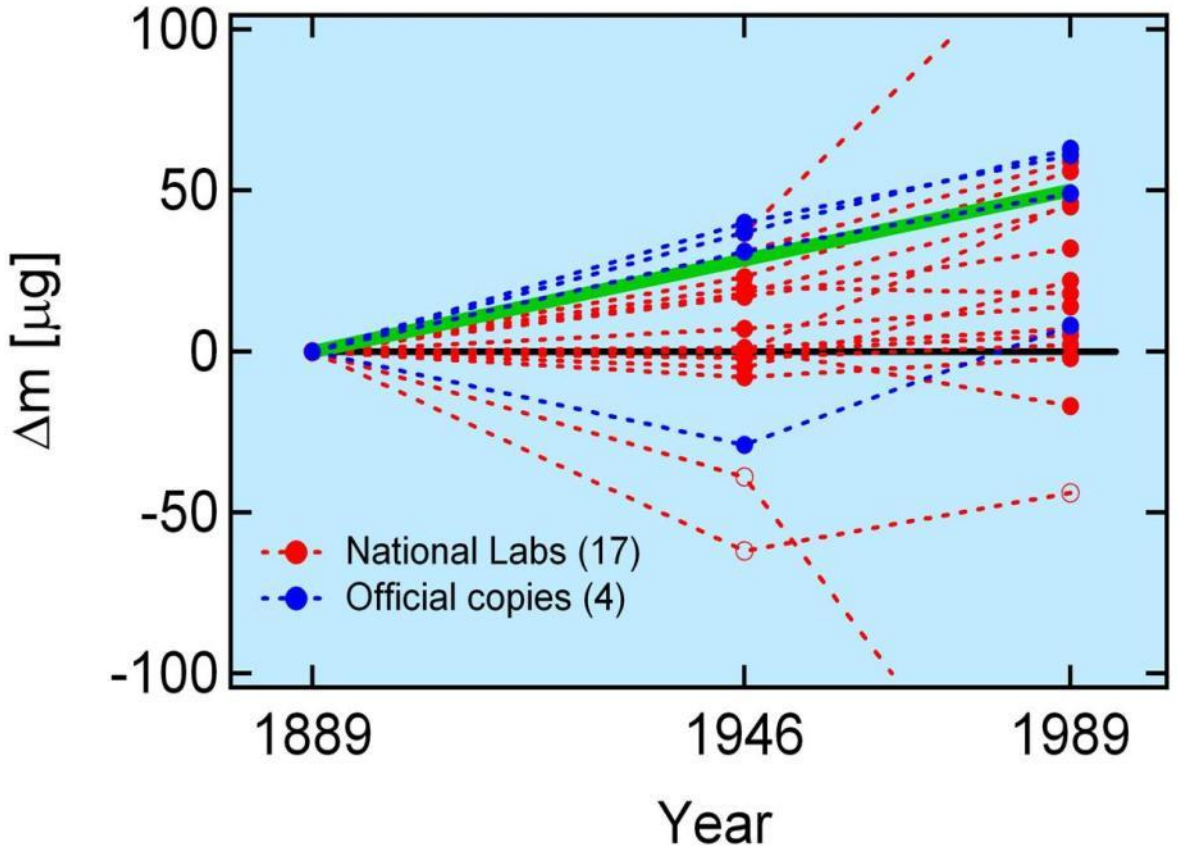


Average mass drift of National Prototypes of the kilogram against the IPK:

~ 50 μg / 100 years

METAS

Results of the 3rd Periodic Verification of National Prototypes of the kg



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

~ 50 μg / 100 years

METAS

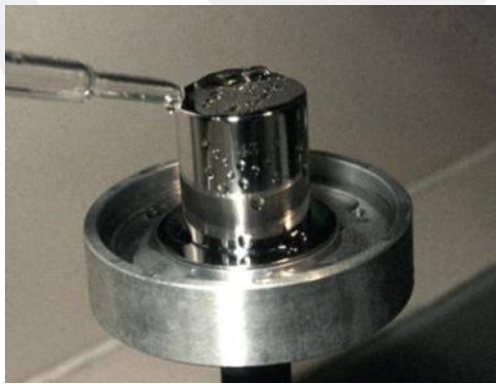
Definition & "mise en pratique"

"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: BIPM cleaning procedure

- Wash with ethanol + ether + chamois leather
- Rinse with steam



METAS

Situation in the mass laboratory

- Prototype #89 (2004)

  u = **5 µg**

- Comparison 2 x 1 kg (Pt-Ir)

  u **< 1 µg**

  ↑

  1 part in 10^9 !!

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

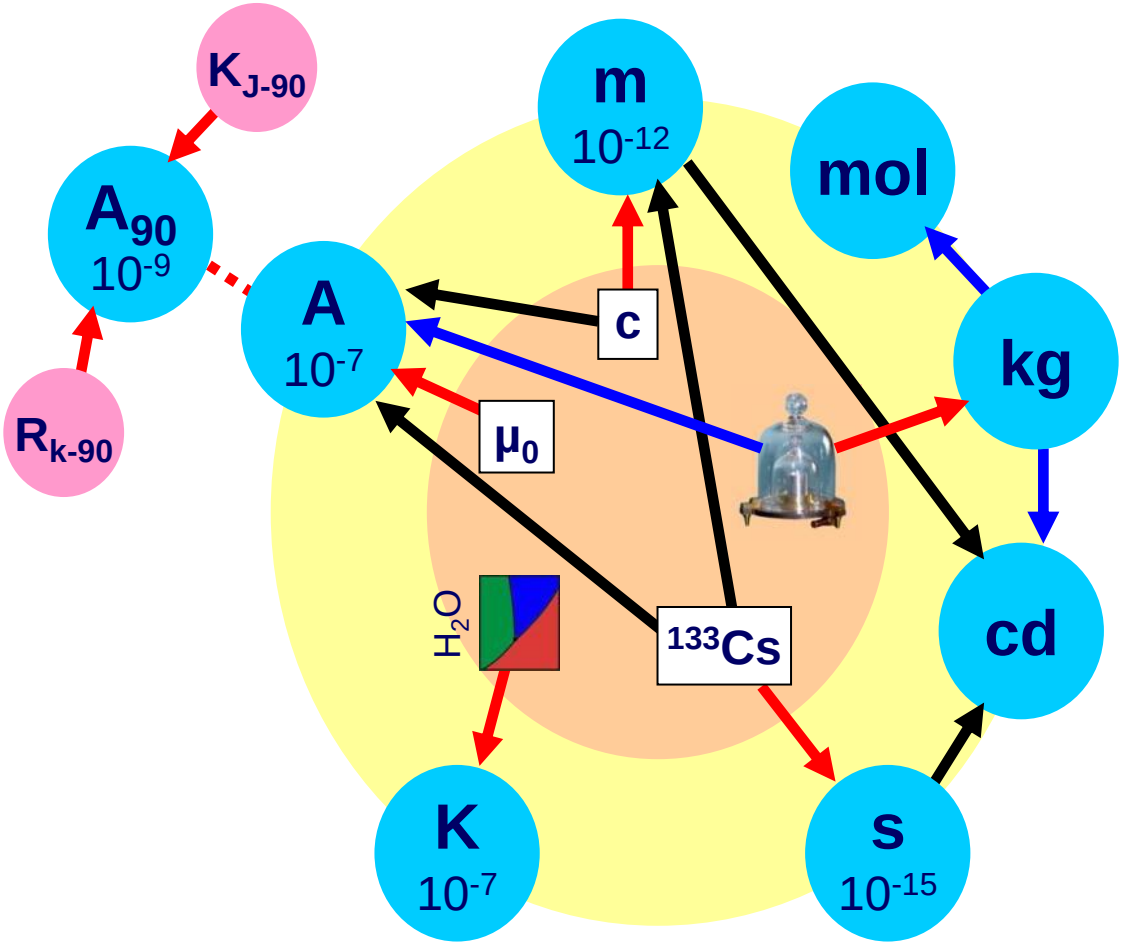
  u **~ 10 µg**

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

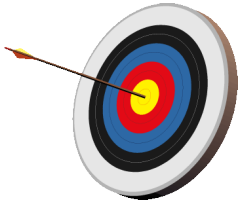
  u **~ 10 µg**

METAS

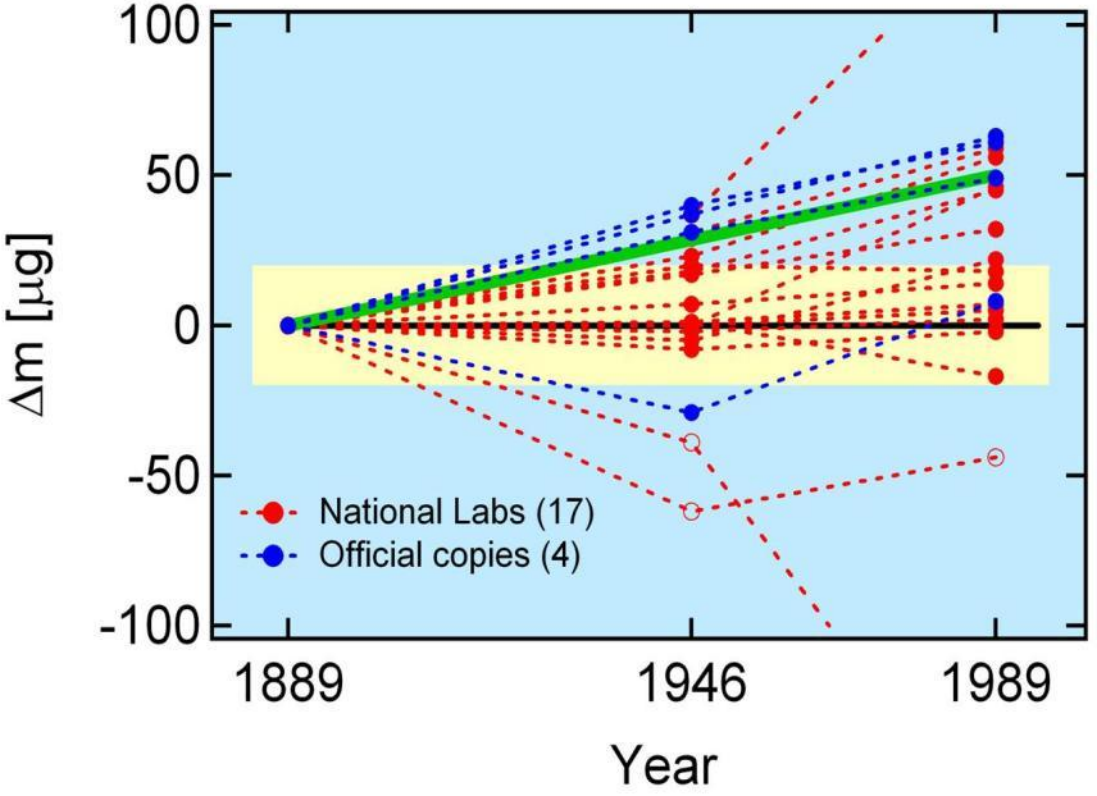
The International System of Units (SI)



New definition of the kg



- Target uncertainty: 2 parts in 10^8



METAS

Towards a new definition of the kg

- Approach **A**

  “From microscopic to macroscopic world…”

  → count atoms

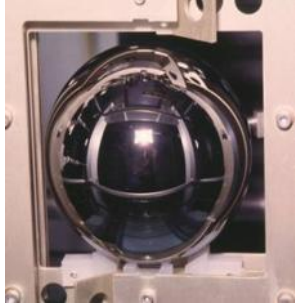
- Approach **B**

  "Benefit from the electrical quantum standards..."

  → Quantum Hall effect (QHE),

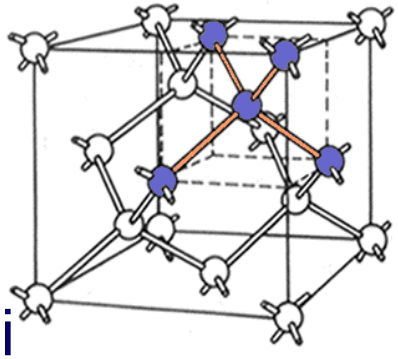
  Josephson effect (JVS).

Towards a new definition of the kg



Approach **A**: "From microscopic to macroscopic world..."
(counting atoms)

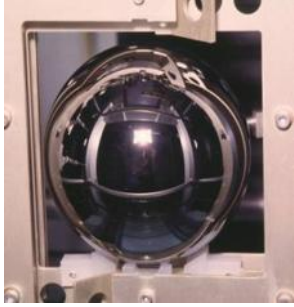
- "Avogadro project" (Si sphere)



$$n_x = 8\frac{V}{a^3}, \quad m = n_x \cdot m_{Si} = n_x \frac{M(Si)}{N_A}$$

$$N_A = \frac{8 \cdot M(Si)}{\left(m/V\right) \cdot a^3}$$

Avogadro Project



$$N_A = \frac{8 \cdot M(Si)}{\left(m/V\right) \cdot a^3}$$

- **M(Si)**: isotopic content (^{28}Si, ^{29}Si, ^{30}Si) measured using mass spectrometry
- **Volume**: interferometric measurement of the sphere
- ***n* = 8** ?: lattice defects, surface effects

Uncertainties:

Natural Si: 3 parts in 10^7

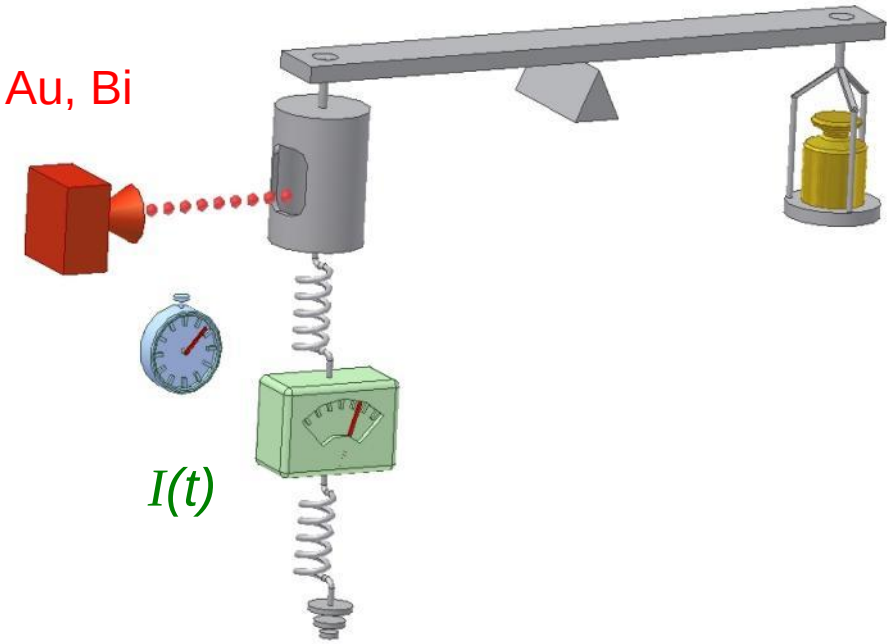
^{28}Si: 3 parts in 10^8

METAS

Towards a new definition of the kg

Approach **A**: "From microscopic to macroscopic world..."
(counting atoms)

- Ion accumulation project (PTB)

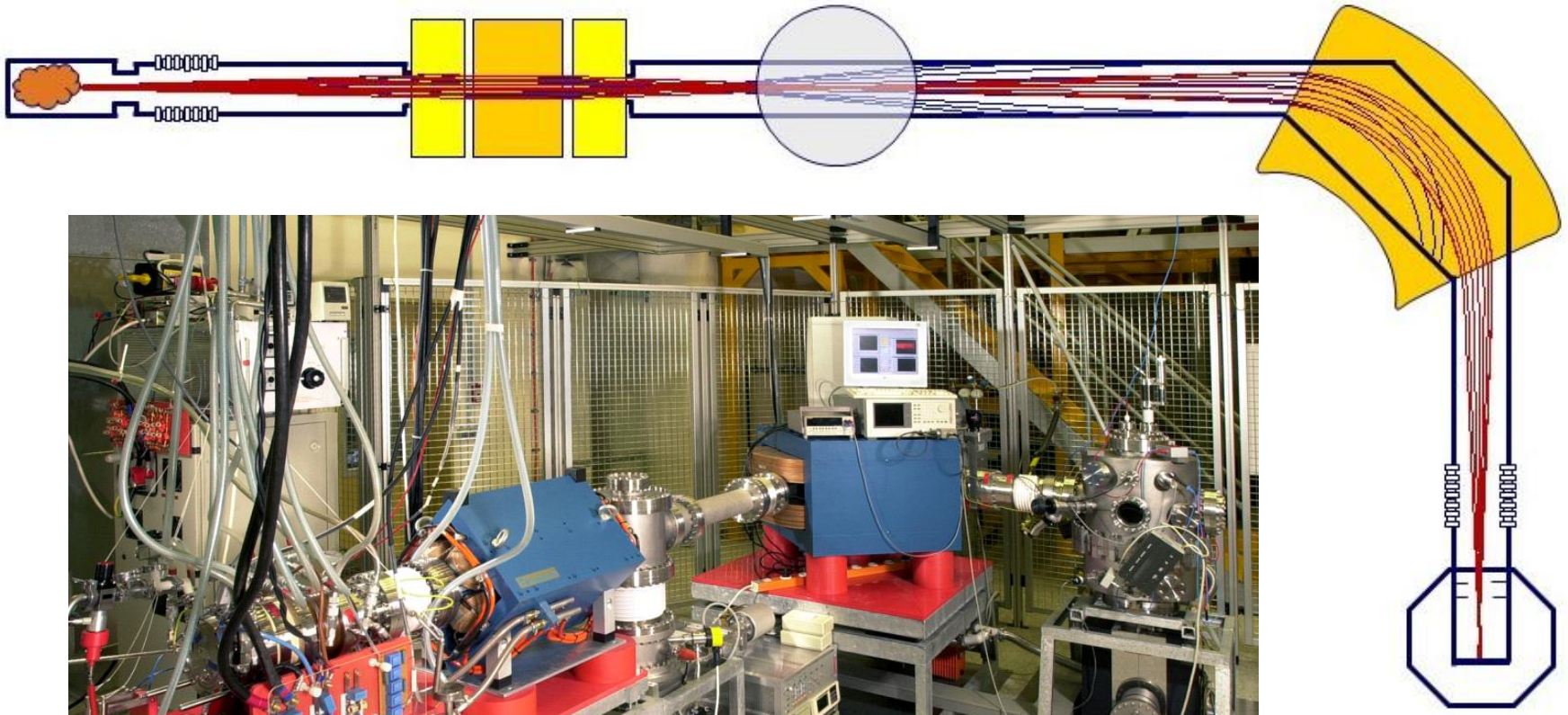


$$m = m_{Au} \cdot \frac{Q}{e} = m_{Au} \cdot \frac{\int I(t)dt}{e}$$

Accumulation rate ~1 g / day
uncertainty: 10^{-4} range

Stopped!

Ion accumulation: Experimental setup



METAS

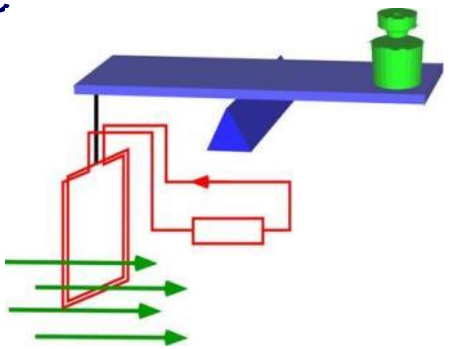
Towards a new definition of the kg

Approach **B**: "Benefit from the electrical quantum standards..."
(QHE, JVS)

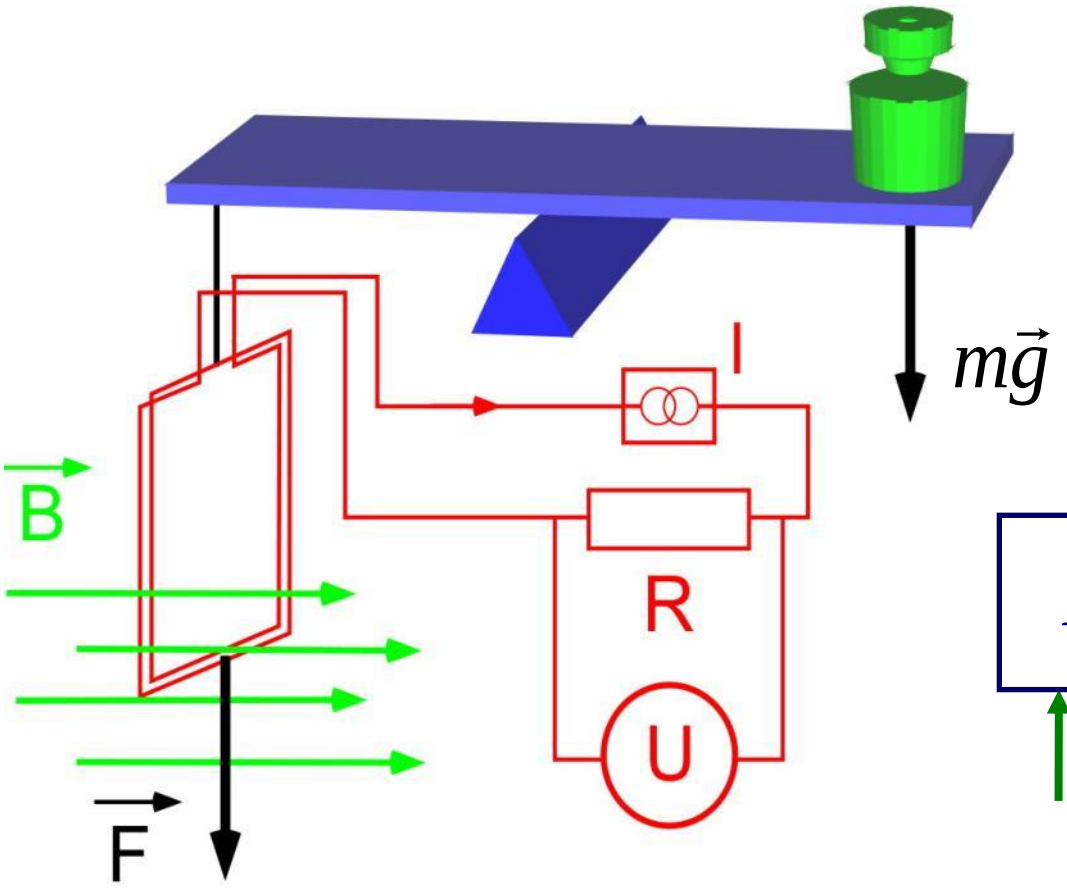
- Voltage balance
  (PTB, University of Zagreb)
- Magnetic levitation
  (NMIJ, VNIIM)

} uncertainty > 1 part in 10^7
Stopped !

- **Watt balance:** establish a link between electrical and mechanical quantities via power equivalence
  (NPL-NRC, NIST, METAS, LNE, BIPM)



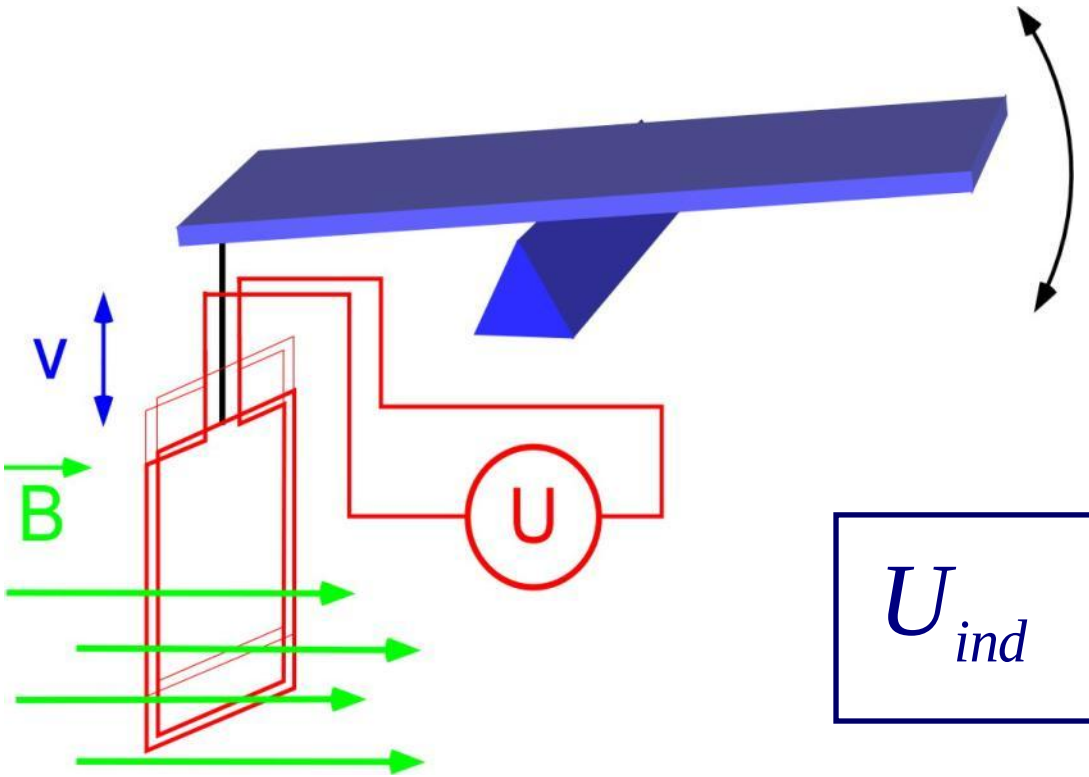
WB Principle (1): static phase / weighing mode



$$I \cdot \int d\ell \times B = mg$$

$$I = \frac{U_j}{R}$$ (QHE & JVS)

WB Principle (2): dynamic phase / velocity mode



$$U_{ind} = v \cdot \int d\ell \times B$$

WB Principle (3): combination of modes

$$G(B,\ell) = \underbrace{\frac{mg}{I}}_{\text{static}} = \underbrace{\frac{U}{v}}_{\text{dynamic}} \Rightarrow \boxed{UI = mgv}$$

electrical power

mechanical power

Only if magnetic field is stable and does not depend on the current

WB Principle (4): combination of modes

Using the expressions from quantum physics (QHE & JVS)

$$U = C_J \cdot U_J = C_J \, n_J \, \frac{h}{2e} \, f_J$$

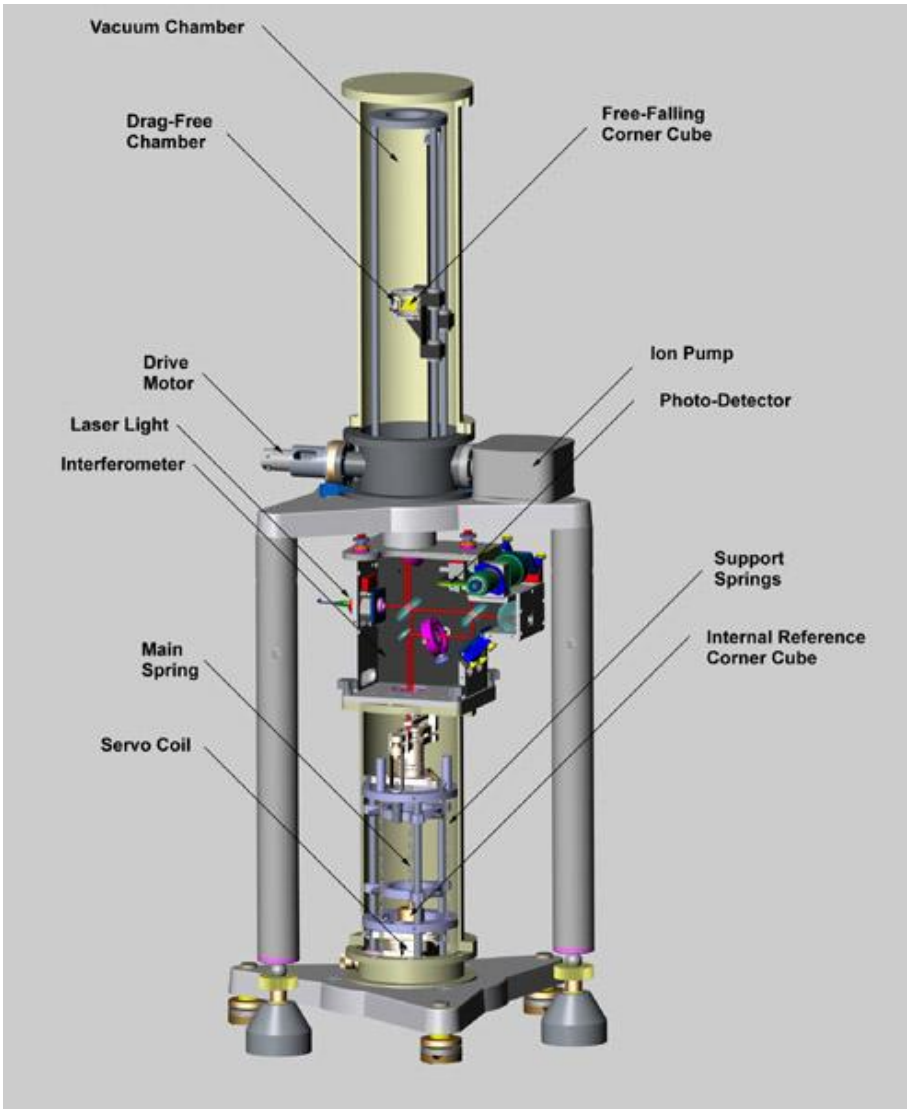
$$R = C_H \cdot R_H = C_H \, \frac{h}{n_H \, e^2}$$

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

$$C = \frac{C_{J1} \, n_{J1} \, C_{J2} \, n_{J2} \, n_H}{4 C_H}$$

"g" measurement: the absolute gravimeter

Free fall trajectory of an optical element in vacuum



$u_r \sim 2 \times 10^{-9}$

Gravimetry: "*g*" at the mass position

- Interpolated value without field distortion

$$g\left(\vec{x}_{ref}\right) = 980588.395\, mGal$$

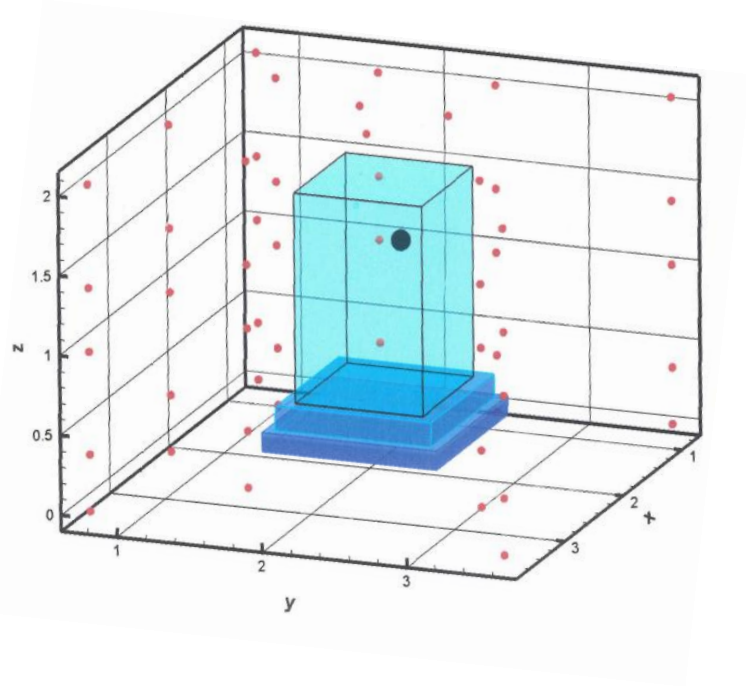
1 µGal = 10^{-9}

- Interpolated value with field distortion

Distortion at the reference position : 3.4 µGal

$$g\left(\vec{x}_{ref}\right) = 980588.398\, mGal$$

Interpolation uncertainty (k=2): 6 µGal



METAS

The projects around the world

1976 The very first watt balance NPL NRC·CNRC

1980 The biggest watt balance + sc magnet NIST

1997 The smallest watt balance METAS

2000 The moving beam watt balance LNE Le progrès, une passion à partager

2002 The single mode watt balance BIPM

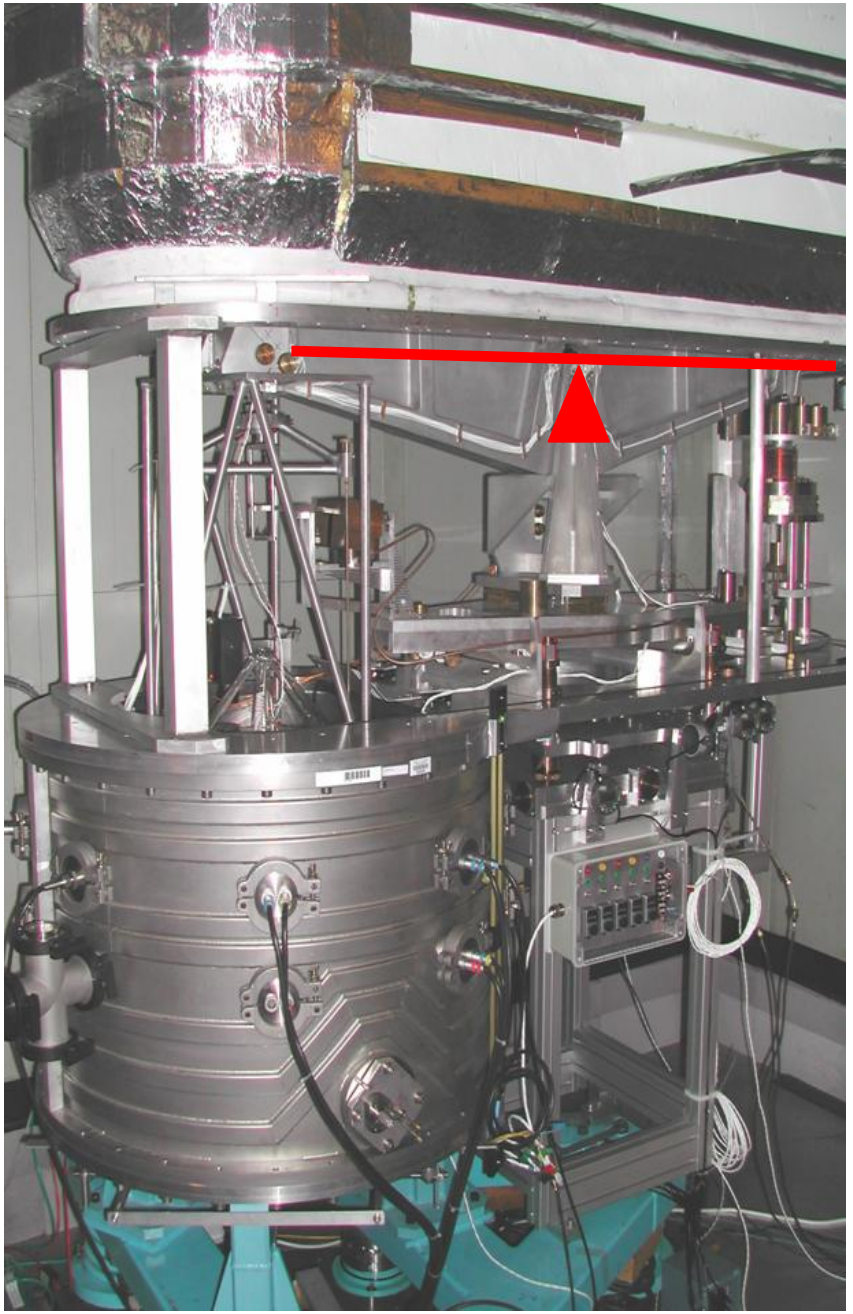
2007 The Joule balance NIM 中国计量科学研究院

Coming soon... MSL (New Zeeland), KRISS (Korea)

METAS

The NPL-NRC Project

0.20 ppm (1988)
0.07 ppm (1990)
0.13 ppm (2010)



METAS

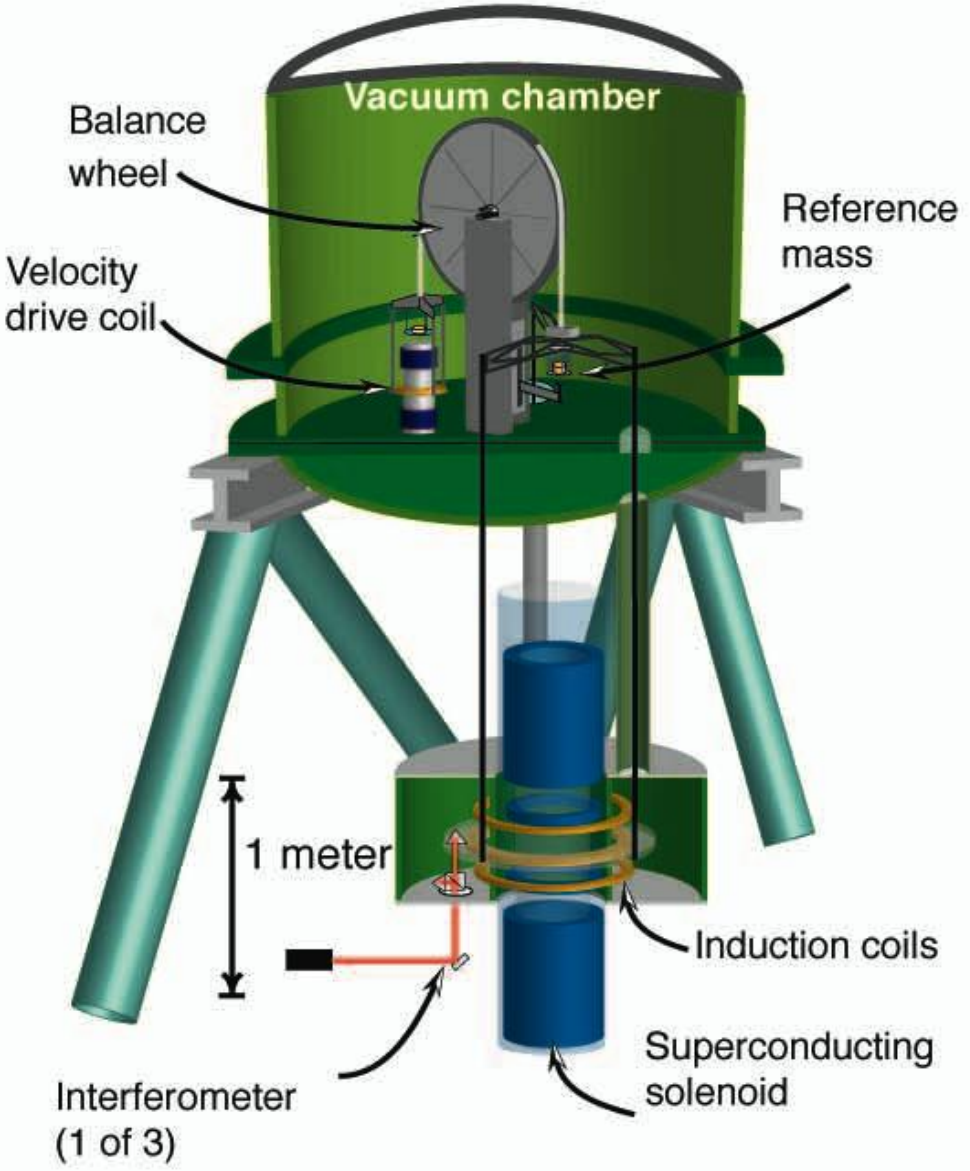
The NIST Project

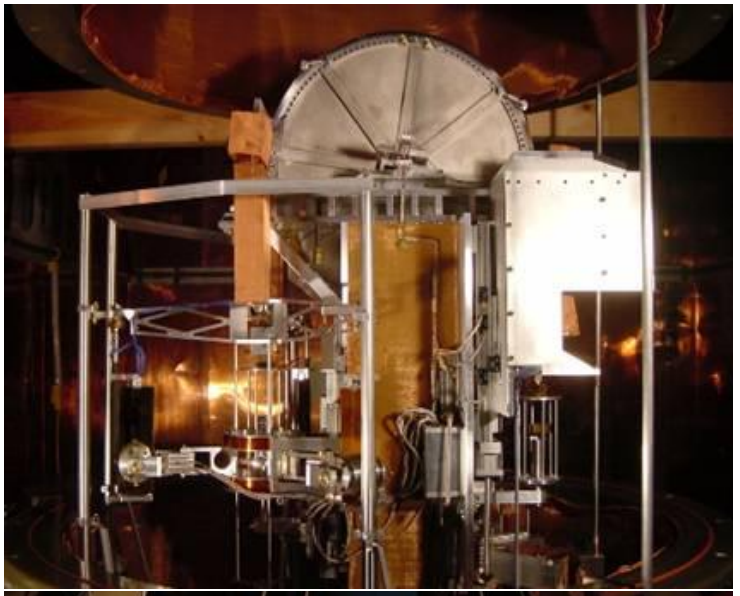
- SC solenoid to produce the field
  - "+" / OFF / "-" **!**
- Wheel balance (knife edge pivot)
- 1 kg and 500 g weighing
- Radial field 0.1 T
- Circular coil (Ø 70 cm)
- Large (height ~ 8 m)
- Non-magnetic building

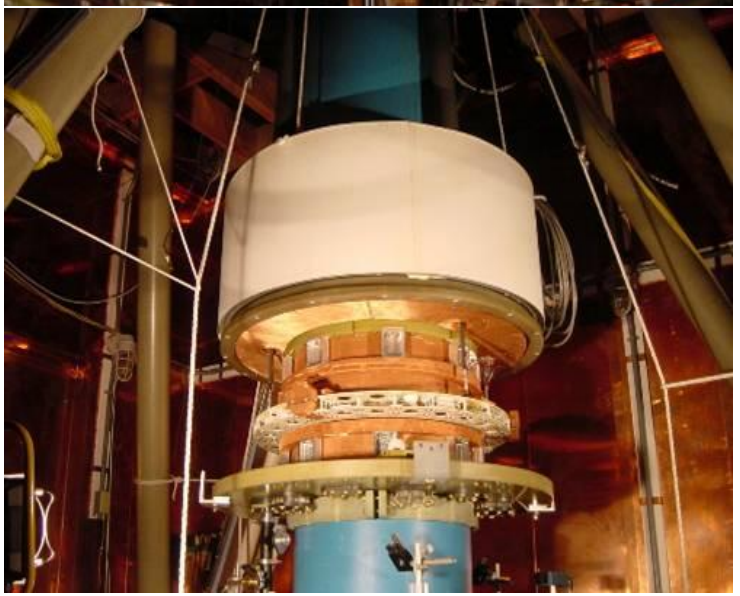
0.09 ppm (1998)
0.057 ppm (2005)
0.036 ppm (2007)

METAS

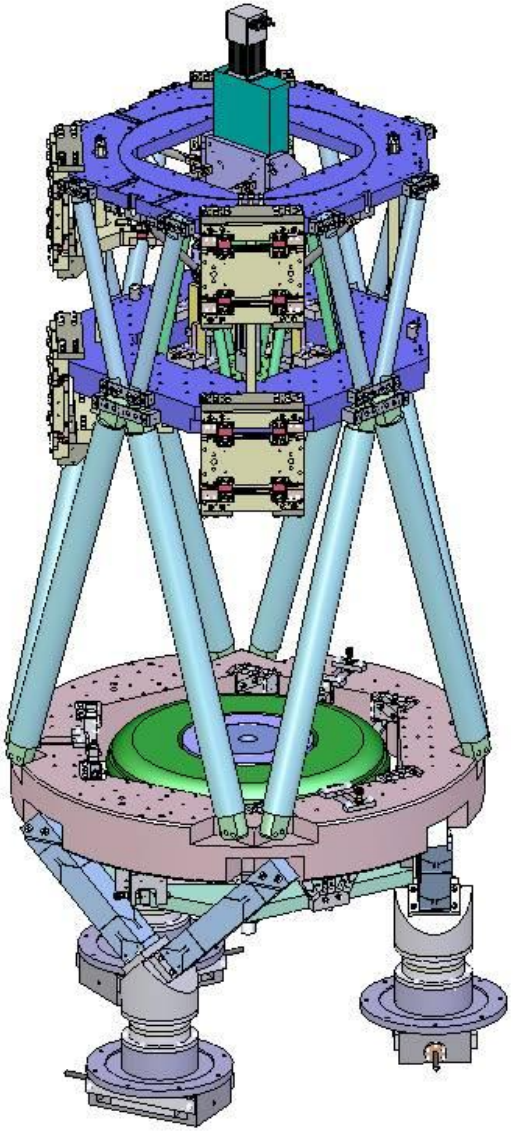
The NIST Project





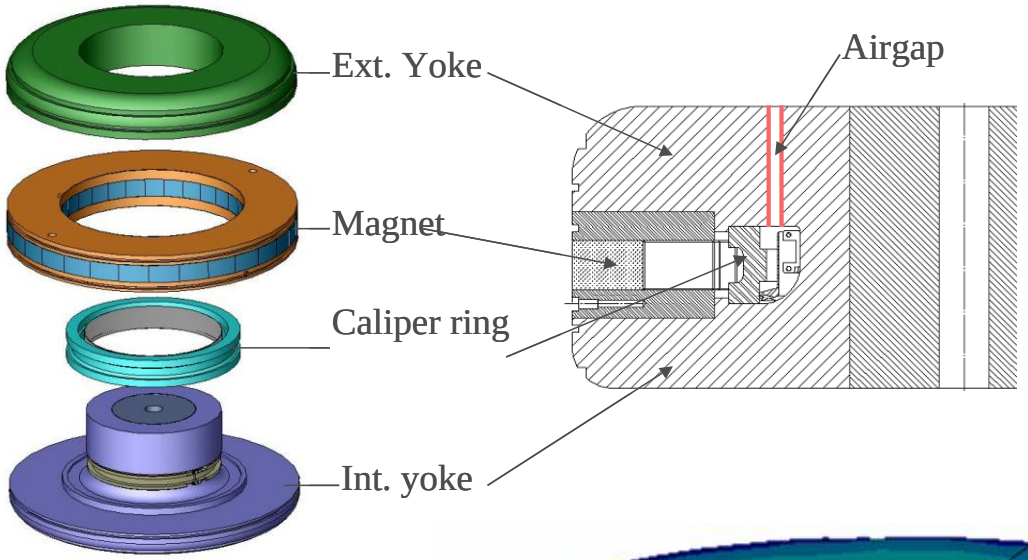


The LNE Project

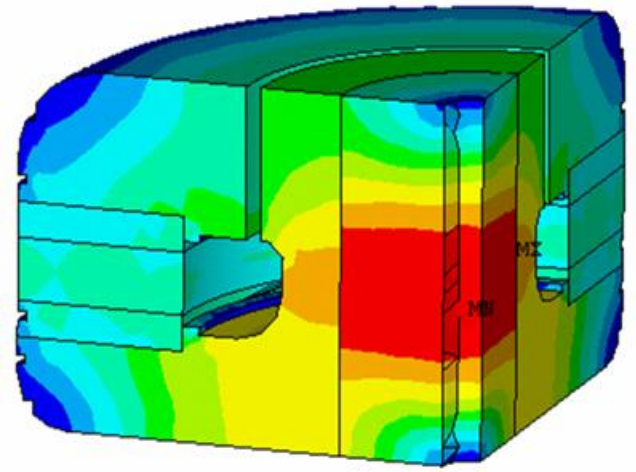


METAS

The LNE Project: The magnet

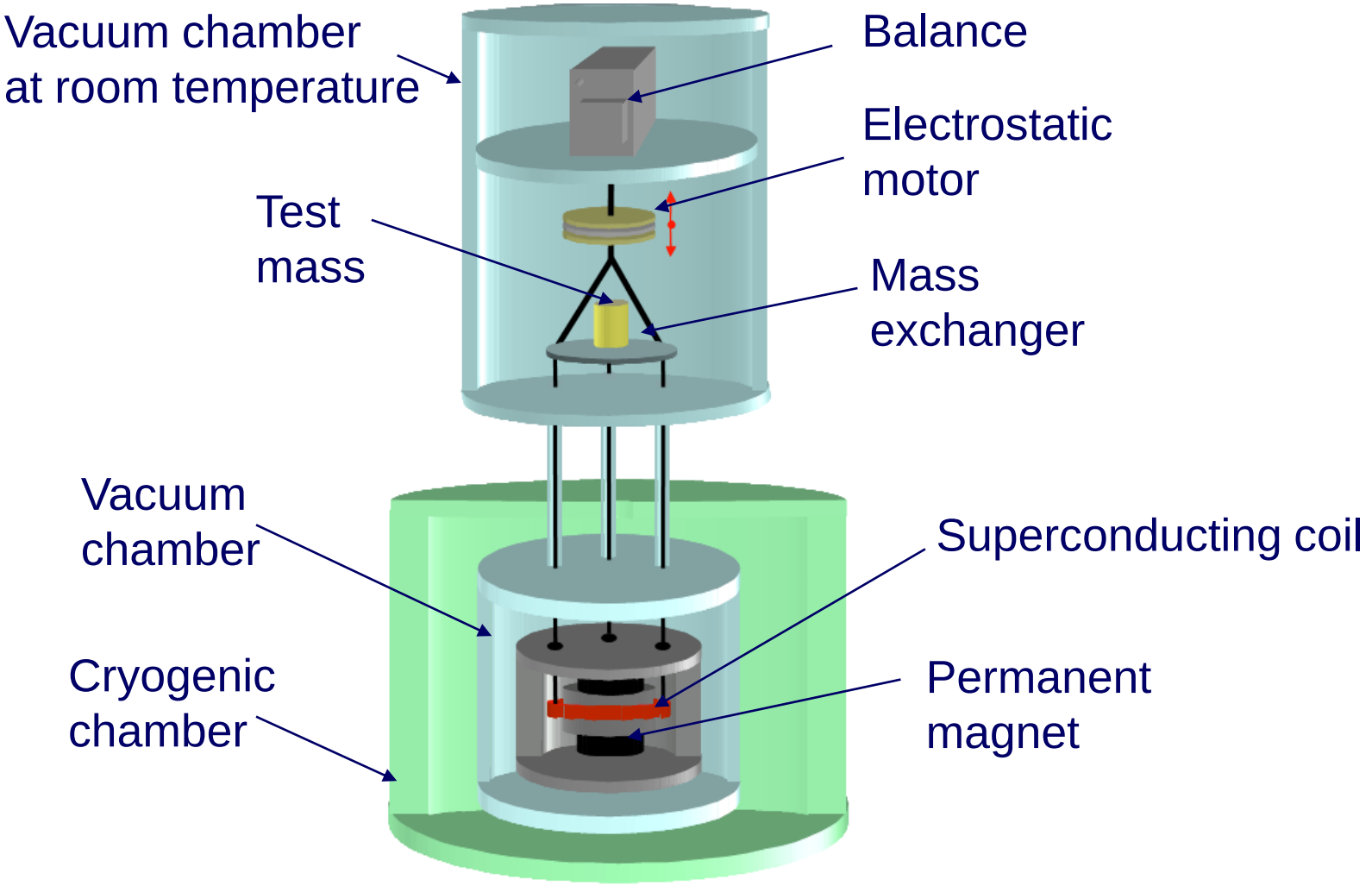


B ~1 T
350 kg



METAS

The BIPM Project: Principle

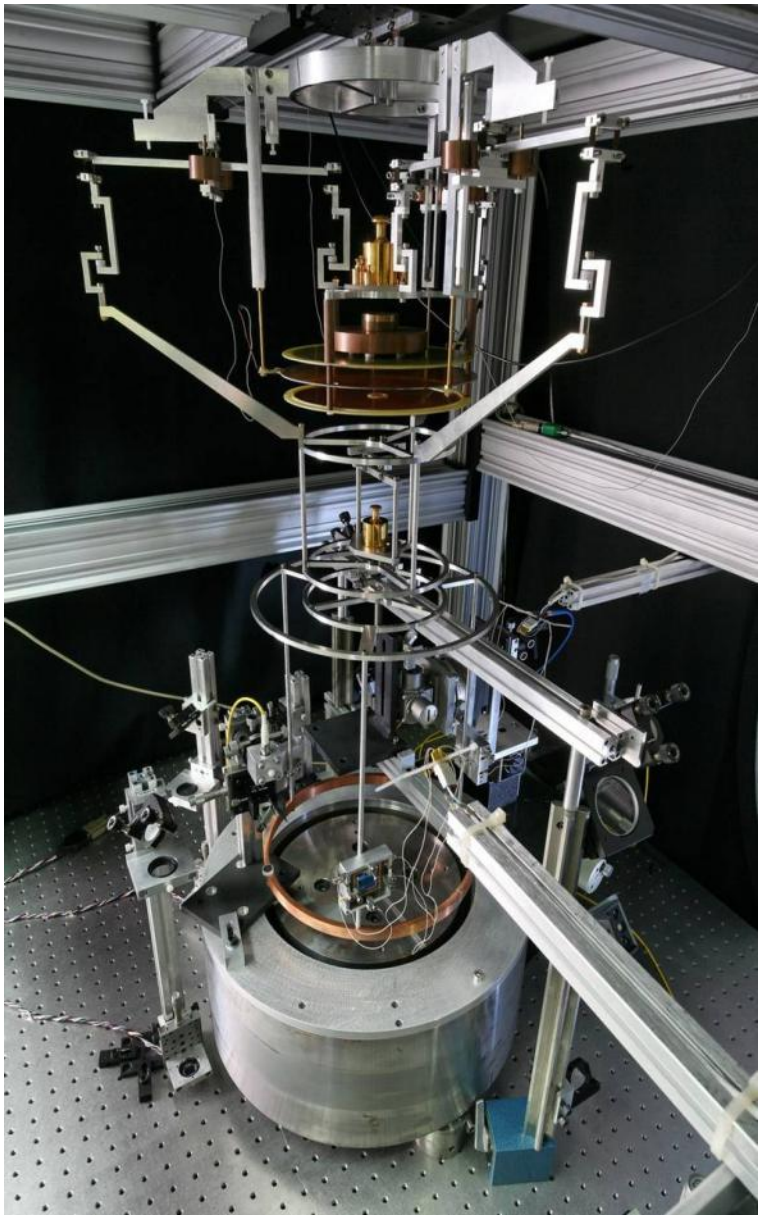


METAS

The BIPM Project

- Simultaneous measurement
- Low temperature
  - Superconducting coil
  - Permanent magnet (radial field)
- Electrostatic expander (motor)
- *Ready for 2015?*

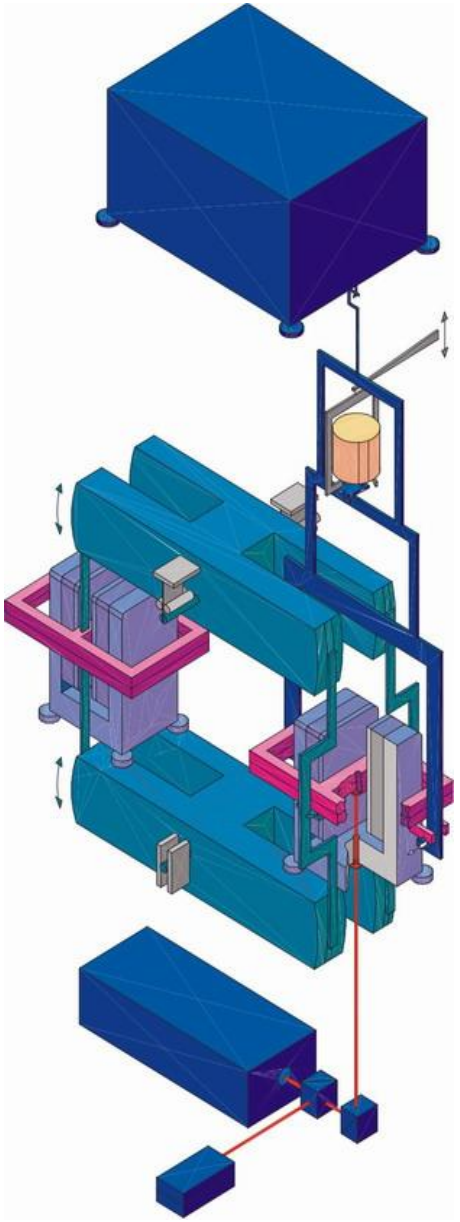
Proposed at CCEM 2002 and WBTM 2003



The METAS Project (BWM I)

- 100 g test mass
- Mass comparator for static phase (Mettler-Toledo modified by Metrotec)
- Permanent magnet

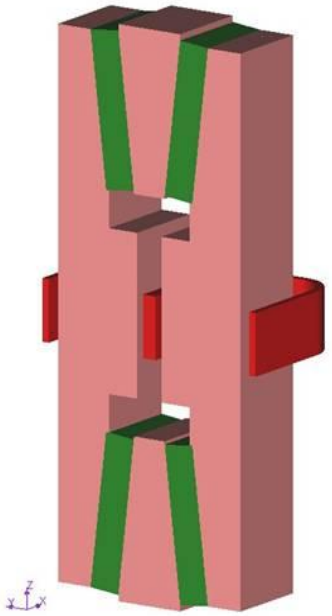
  homogenous parallel field (0.6 T)
- Coil: 8-shape (8x8 cm)
- Independent mechanical system for the dynamic phase
- Small (T stabilization, vibration,…)

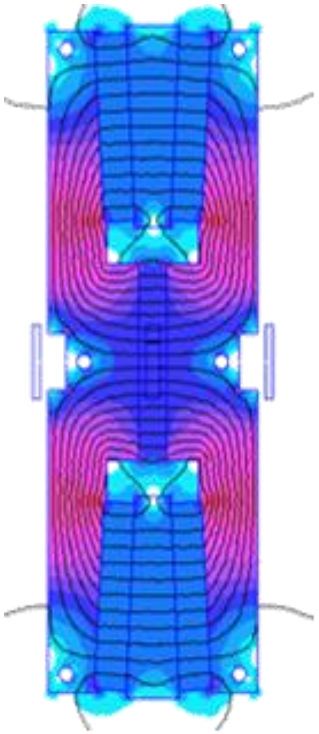


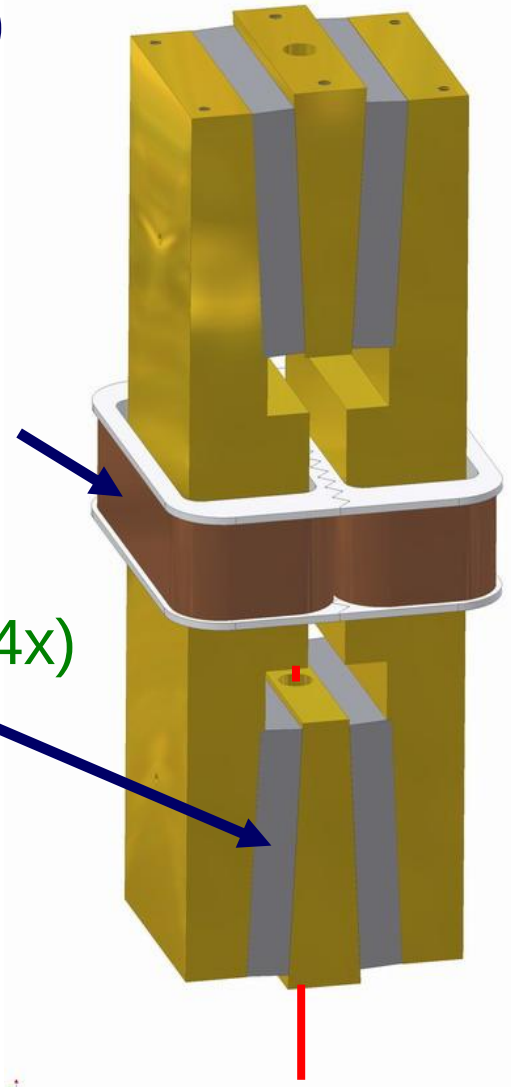
METAS

BWM I: The Magnet

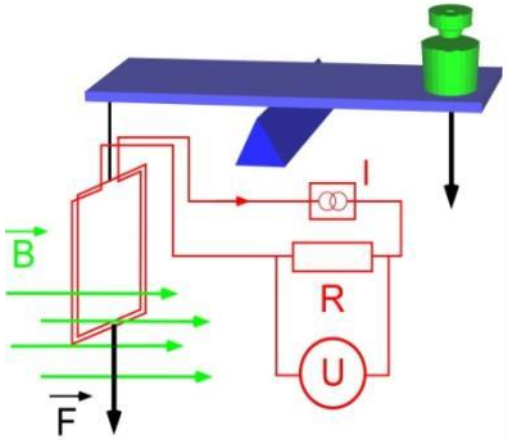
- Permanent magnet (2nd generation)
  - B ~ 0.6 T
  - Open geometry (adjustable)
  - 8-shape coil

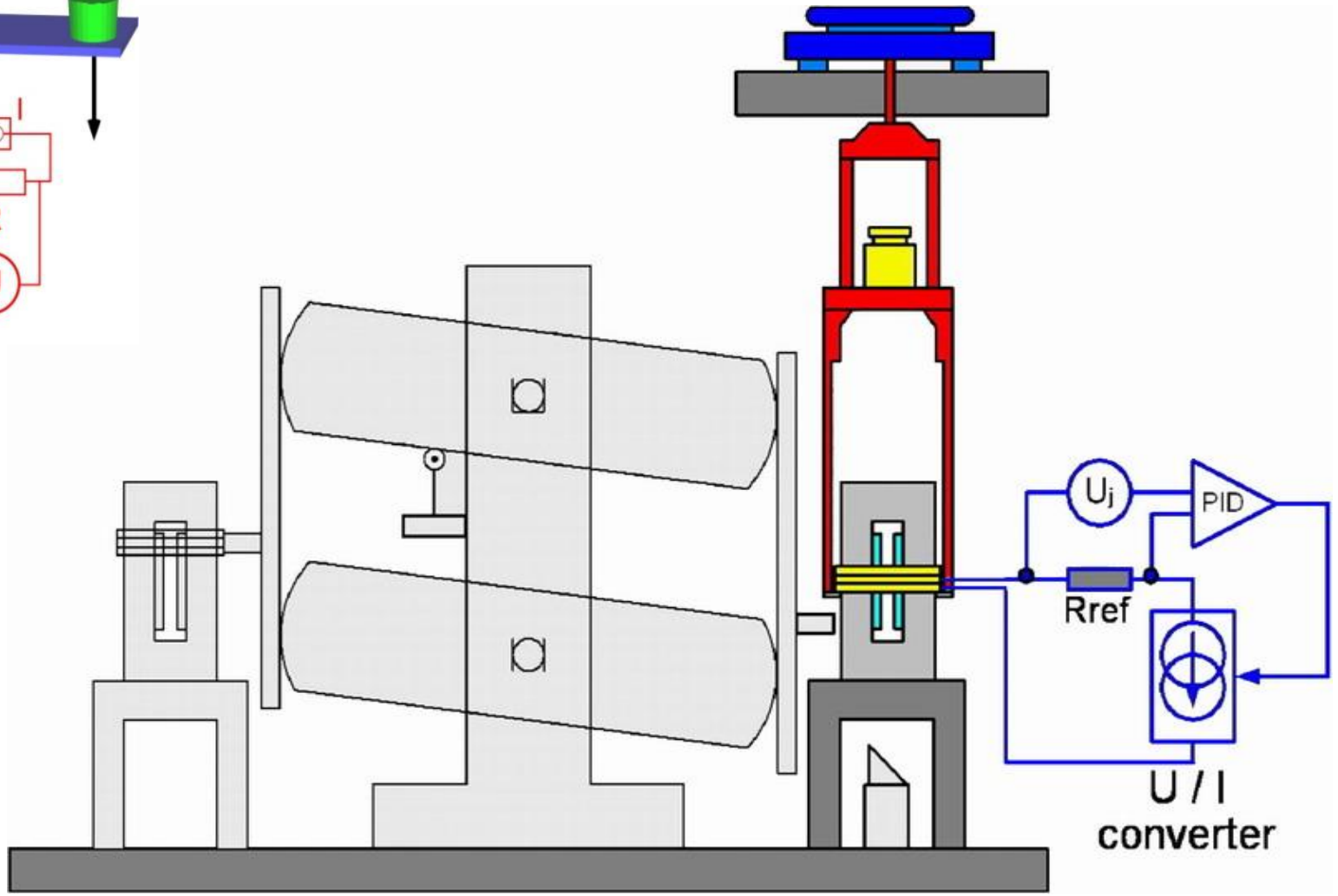






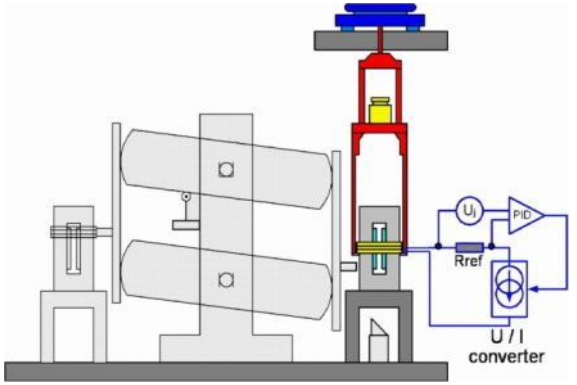
BWM I: Static phase





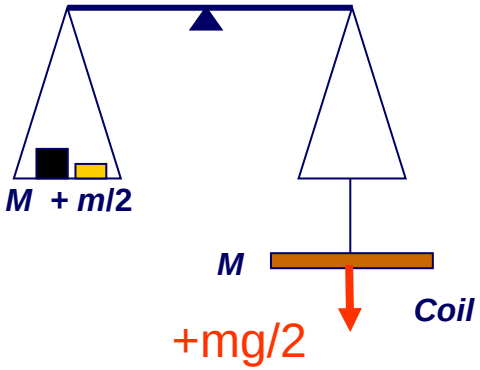
METAS

The static phase

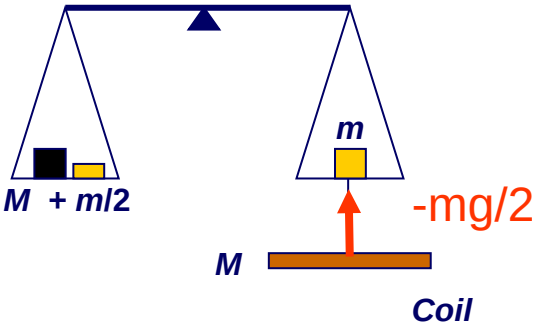


- Combination of W^- and W^+

W^- (I<0)

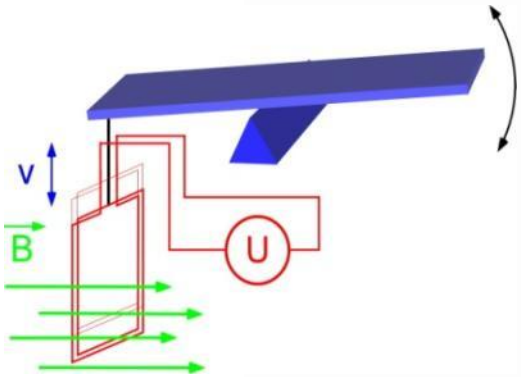


W^+ (I>0)



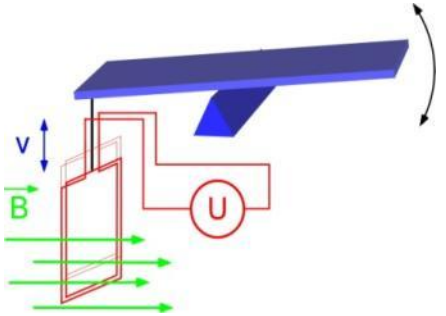
METAS

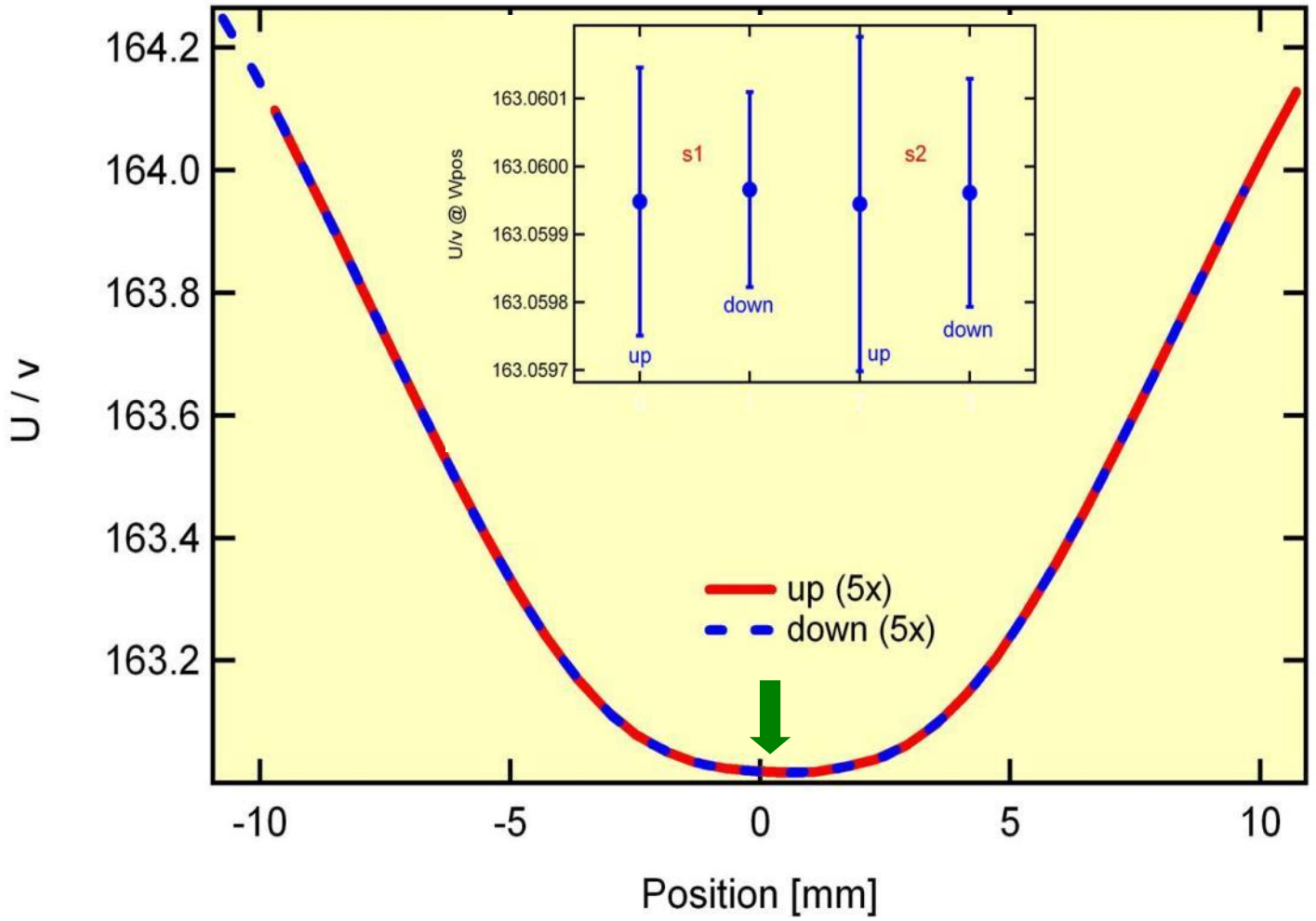
BWM I: Dynamic phase

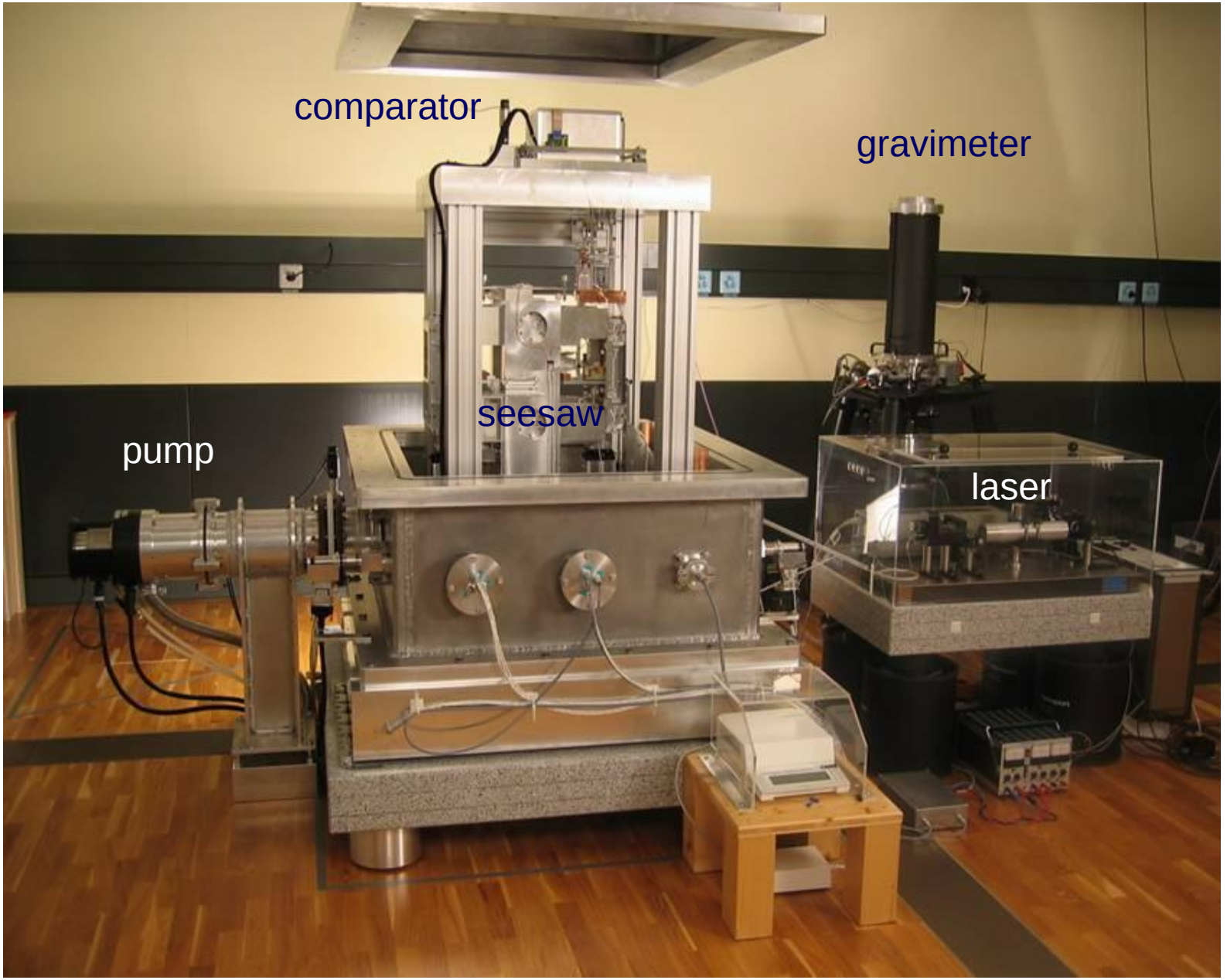


Coil position
@ W_{pos}

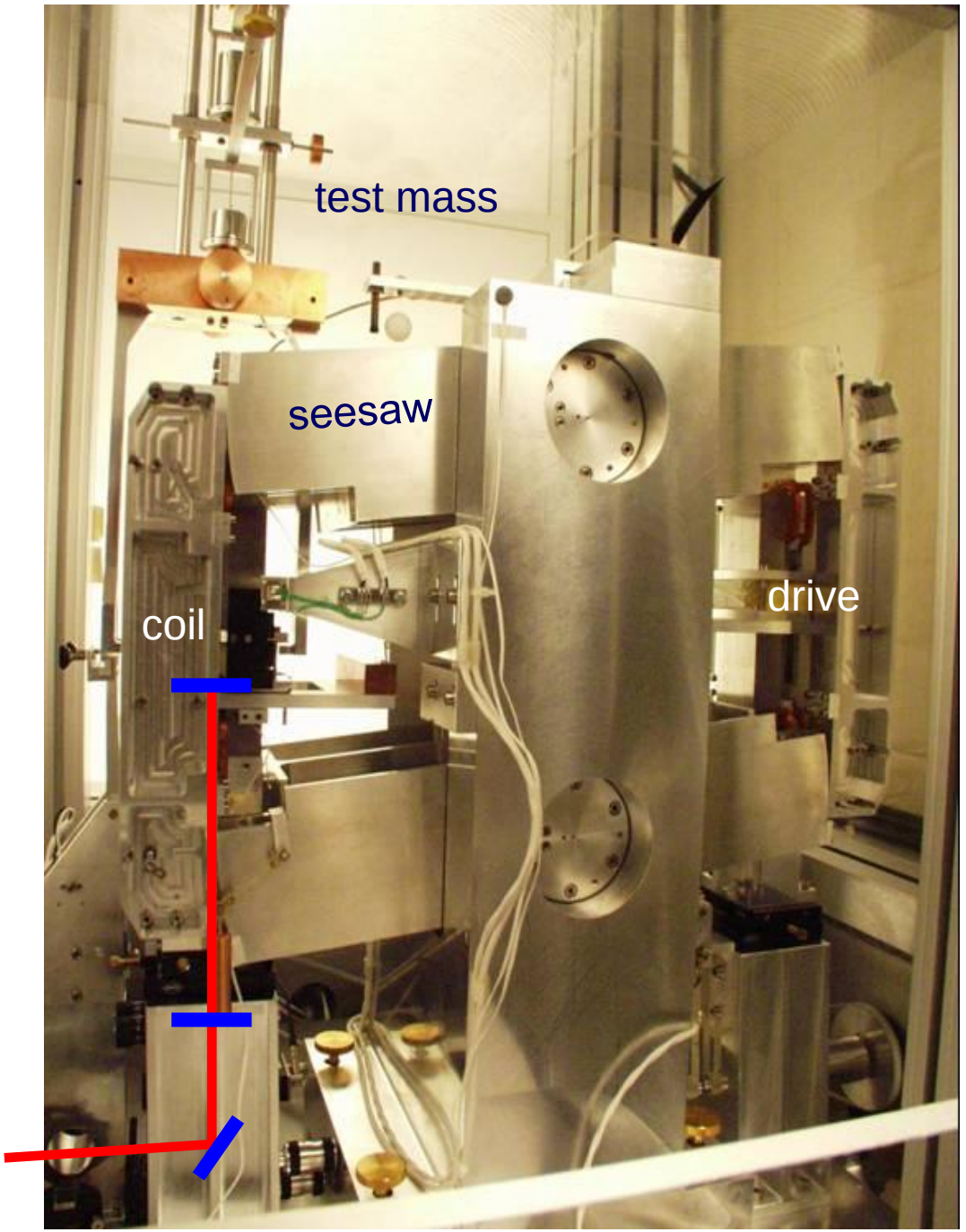
The dynamic phase



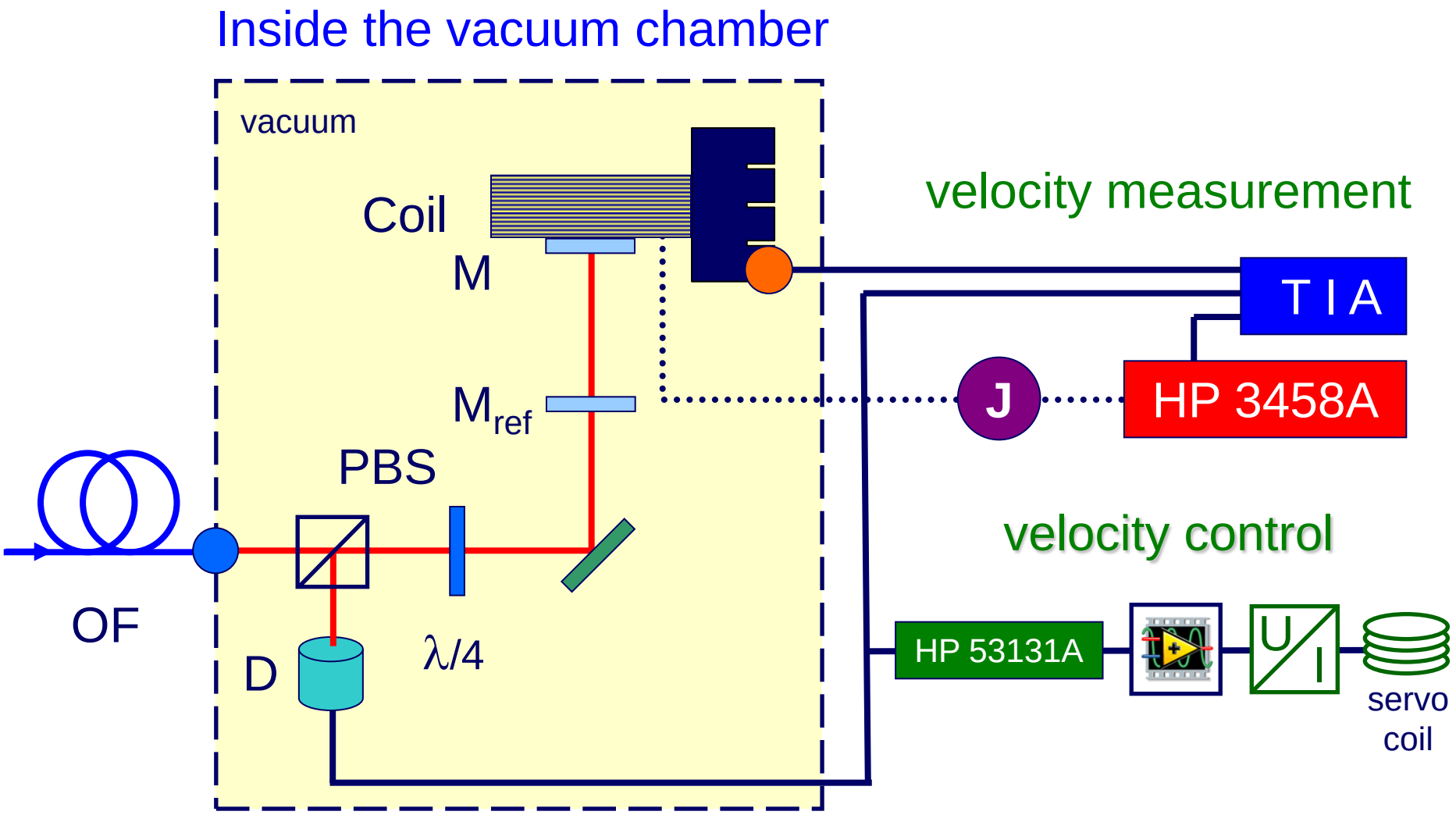




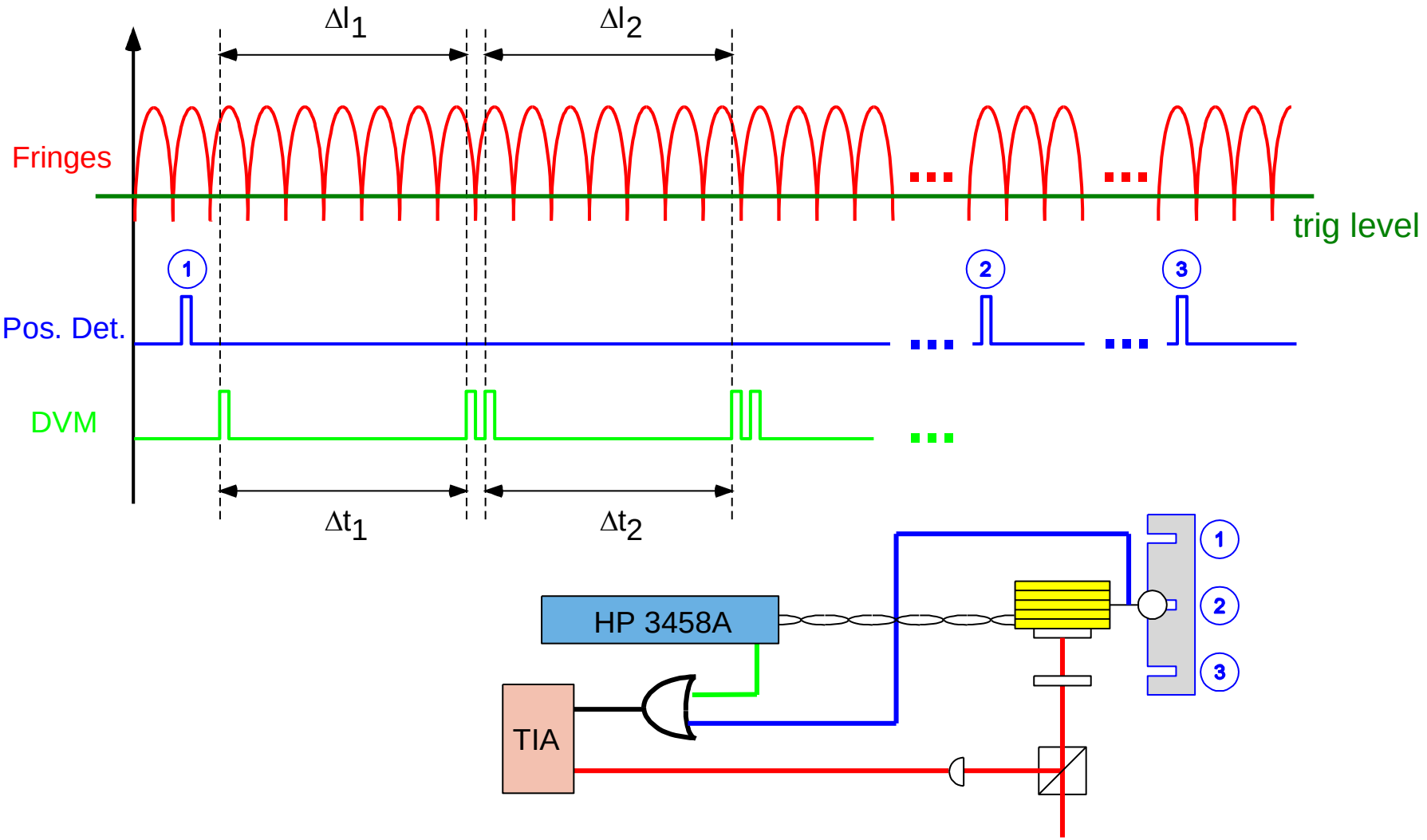
METAS


test mass
seesaw
coil
drive

Interferometer system

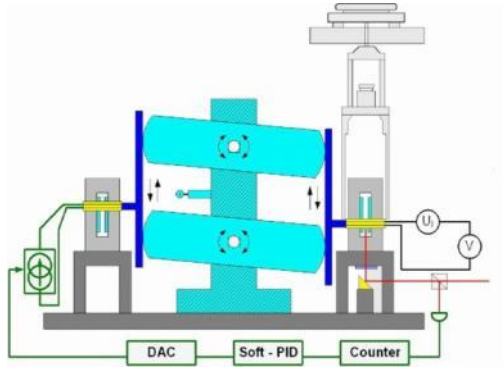


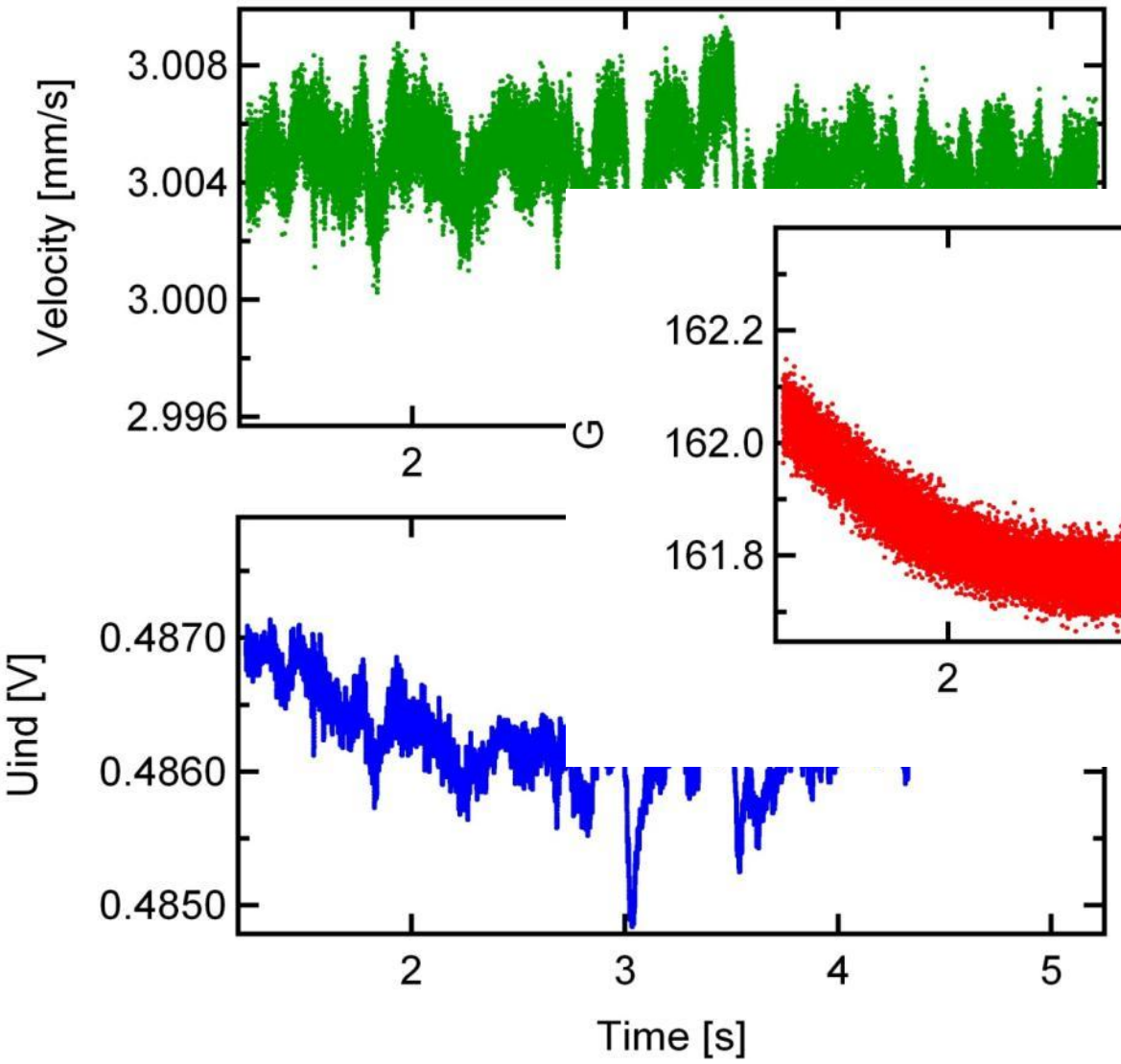
Dynamic phase: Synchronization



METAS

U/v ratio



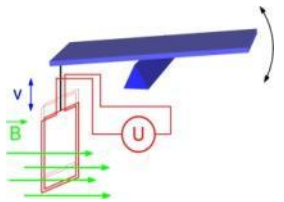


METAS

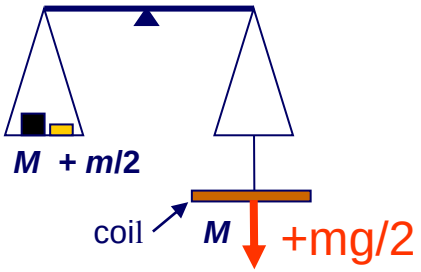
Measurement sequence (@ METAS)

$W_+ \; W_- \quad U_{ind}^{(-)} \quad W_- \; W_+ \; W_- \; W_+ \quad U_{ind}^{(+)} \quad W_+ \; W_-$

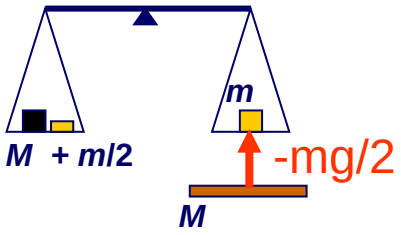
- where: U_{ind} Induced voltage measurement (5 up&down)



W-



W+

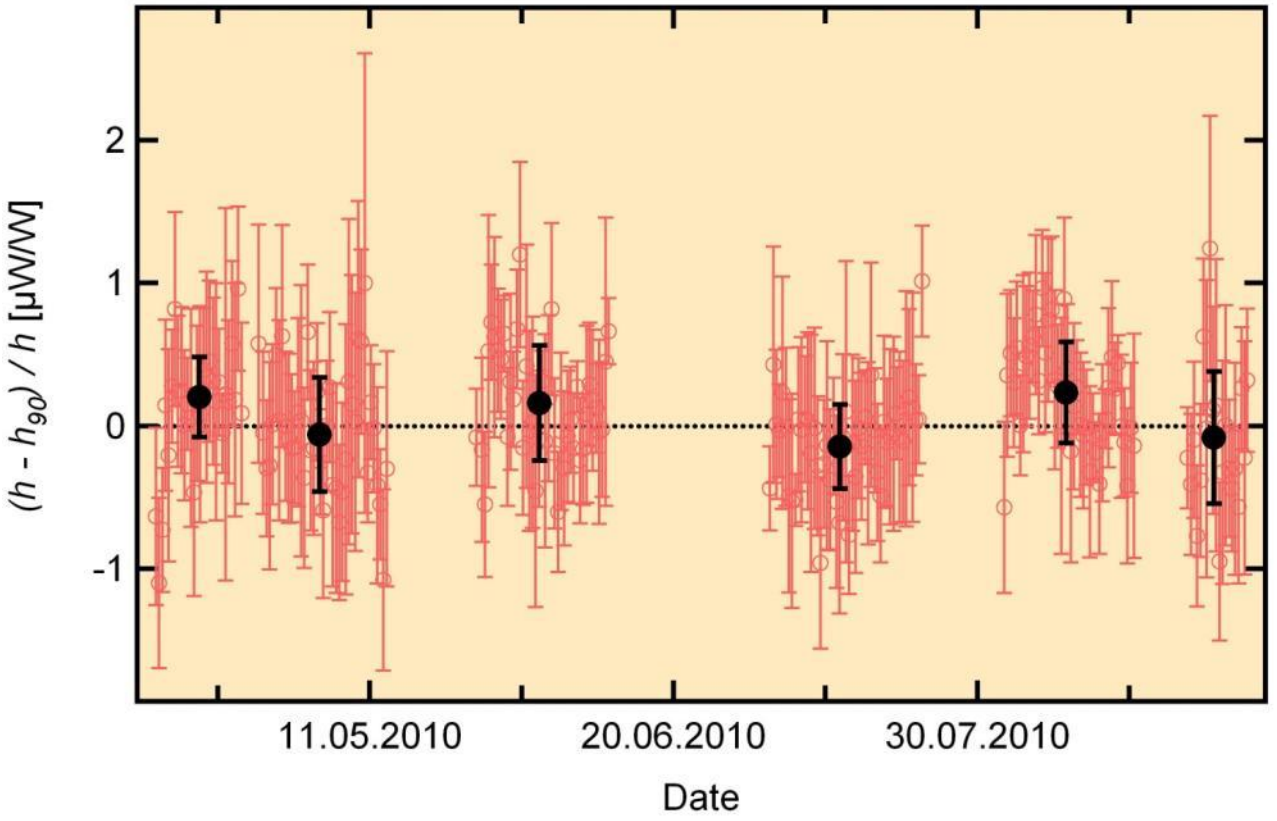


- Time symmetry !
- Acceleration of gravity *g* measured synchronously
- Duration: ~60 minutes

METAS

BWM I Project: Results

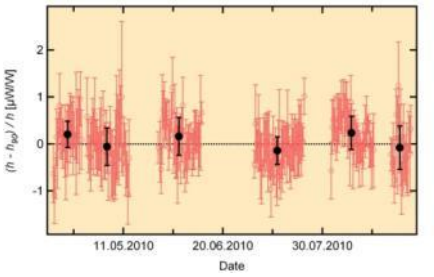
- Determination of the Planck constant



- 3400 h
- 100 g AuCu
- p(air) = const
- Published in *Metrologia* ***48***, *133-141 (2011)*

h = 6.626 069 1(20) ·10^{34} Js [0.29·10^{-6}]

BWM I: Uncertainty budget



	Contributions	[µW/W]
	Reproducibility	0.07
	Operation at atm. pressure	0.09
	Magnet temperature stability	0.05
	Voltage measurements	0.10
	U/v ratio at weighing position	0.11
*	F/I determination	0.12
*	Beam angle	0.12
*	Horizontal motion	0.10
	Other contributions	0.10
	Combined uncertainty	**0.29**
*	Alignment	0.20

METAS

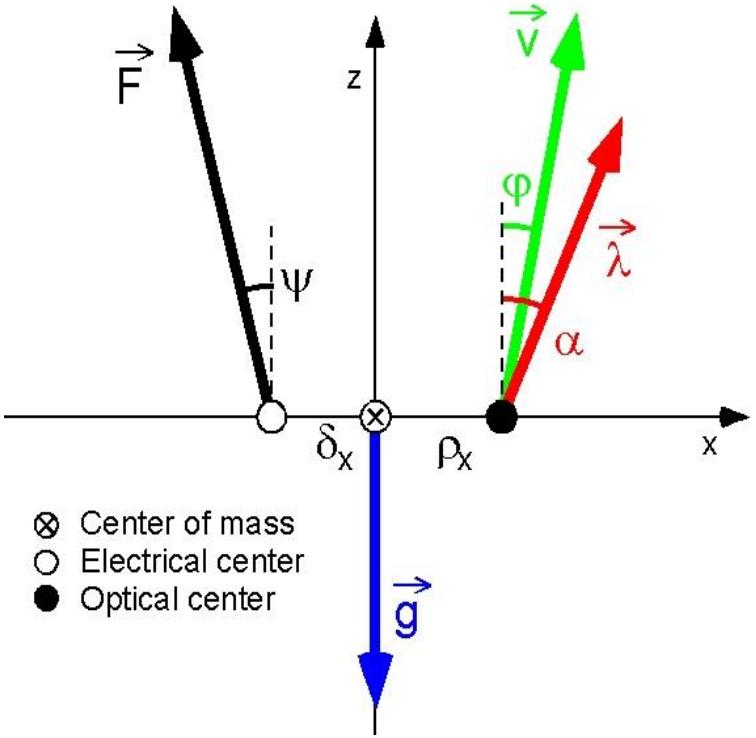
The alignment issue

Velocity vector $\vec{v}$

Laser beam $\vec{\lambda}$

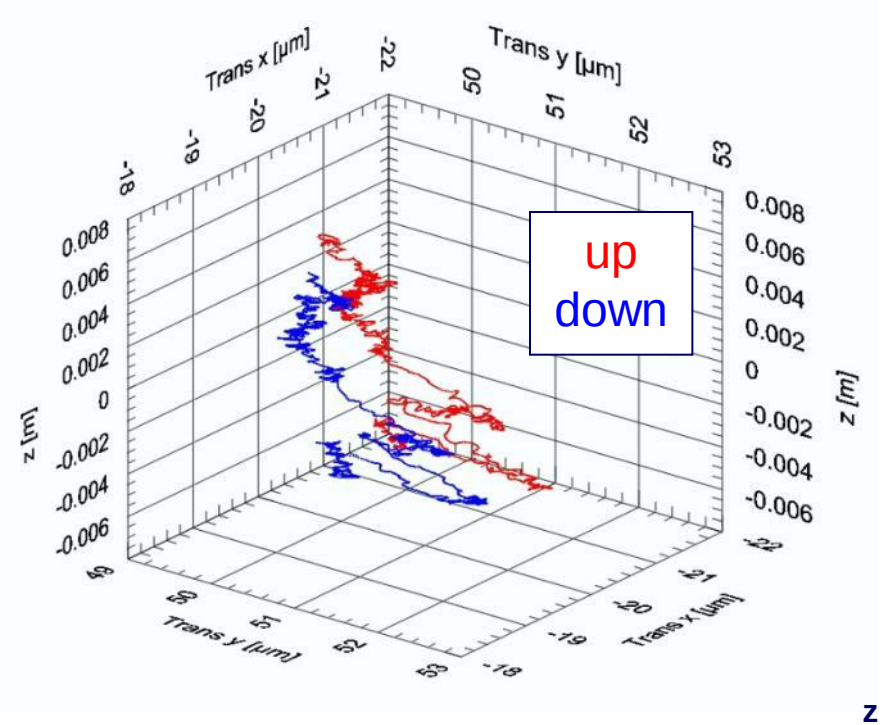
Acceleration of gravity $\vec{g}$
(vertical reference)

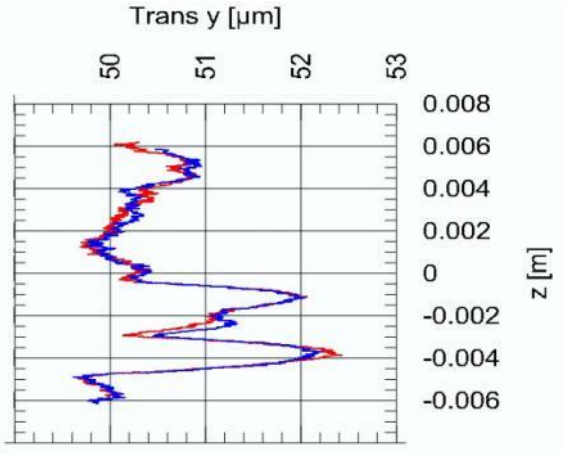
Target uncertainty: ~10 µrad

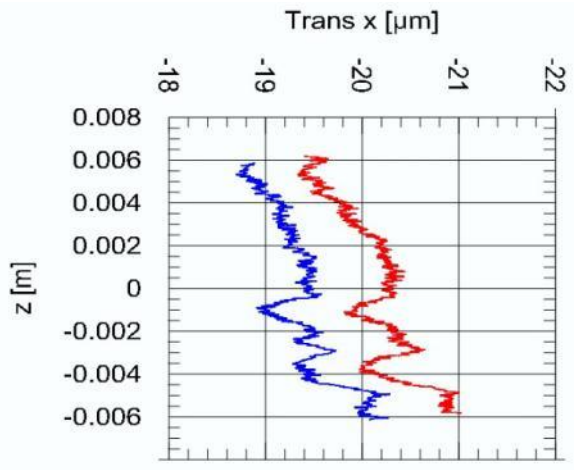


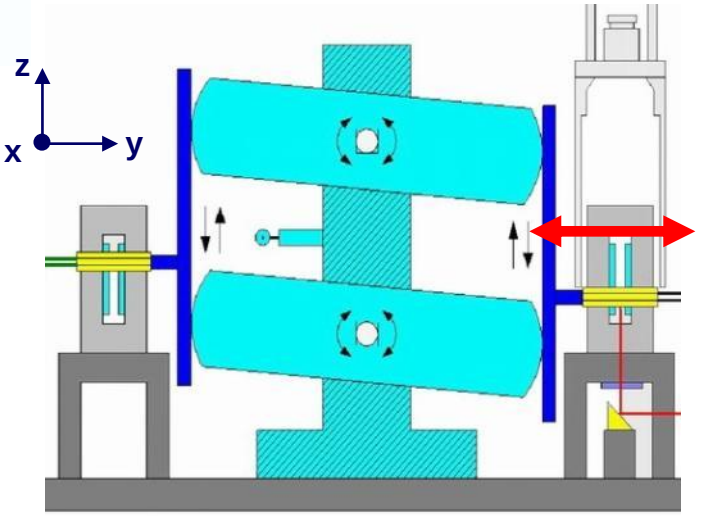
METAS

Coil attitude: Trajectory









The BWM II Project

- Timescale: 2008 - 2012 Construction & evaluation
  2013 - 2015 Measurement

- Main Partners:
  CERN (Magnet group): New magnetic circuit
  EPFL (PhD @ LSRO): New mechanical system
  Mettler-Toledo (R&D): New cell

- Other partners:
  Uni ZH, BFH-TI: Bachelor & Master works
  CIFOM: machining facilities (Wire EDM)
  Mecartex / Heidenhain
  Université Polytechnique de Montréal (Canada)

BWM II Project: Load cell

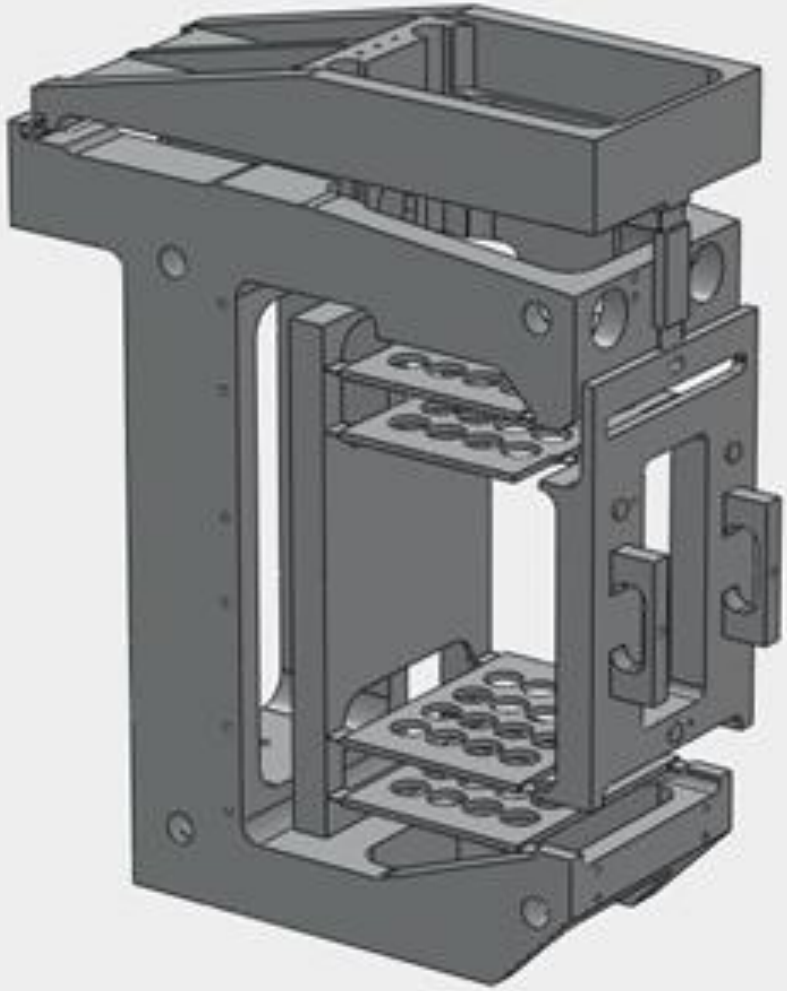
- Tests started at Mettler-Toledo
  in air and in vacuum
- Nominal load: 1200 g
- Range: ± 4 g
- Resolution: 0.4 µg
- Cell Weight: 1.28 kg

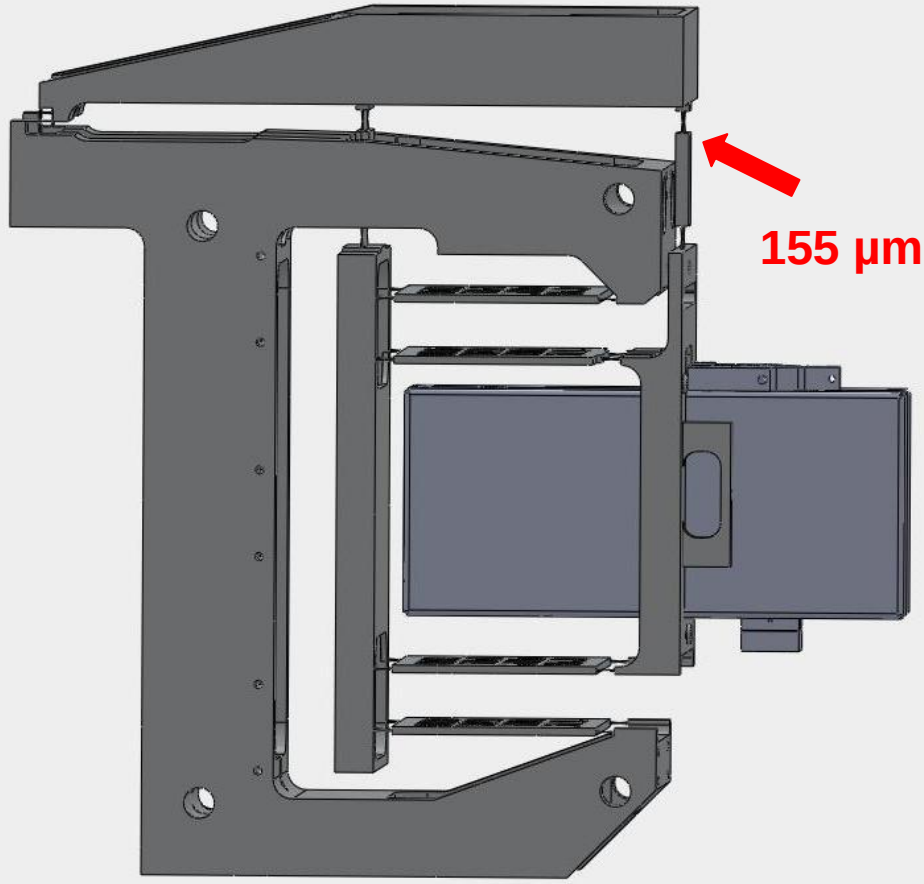
METAS

BWM II Project: Mechanical system

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- 13-hinge stage
  - 1st prototype at METAS !





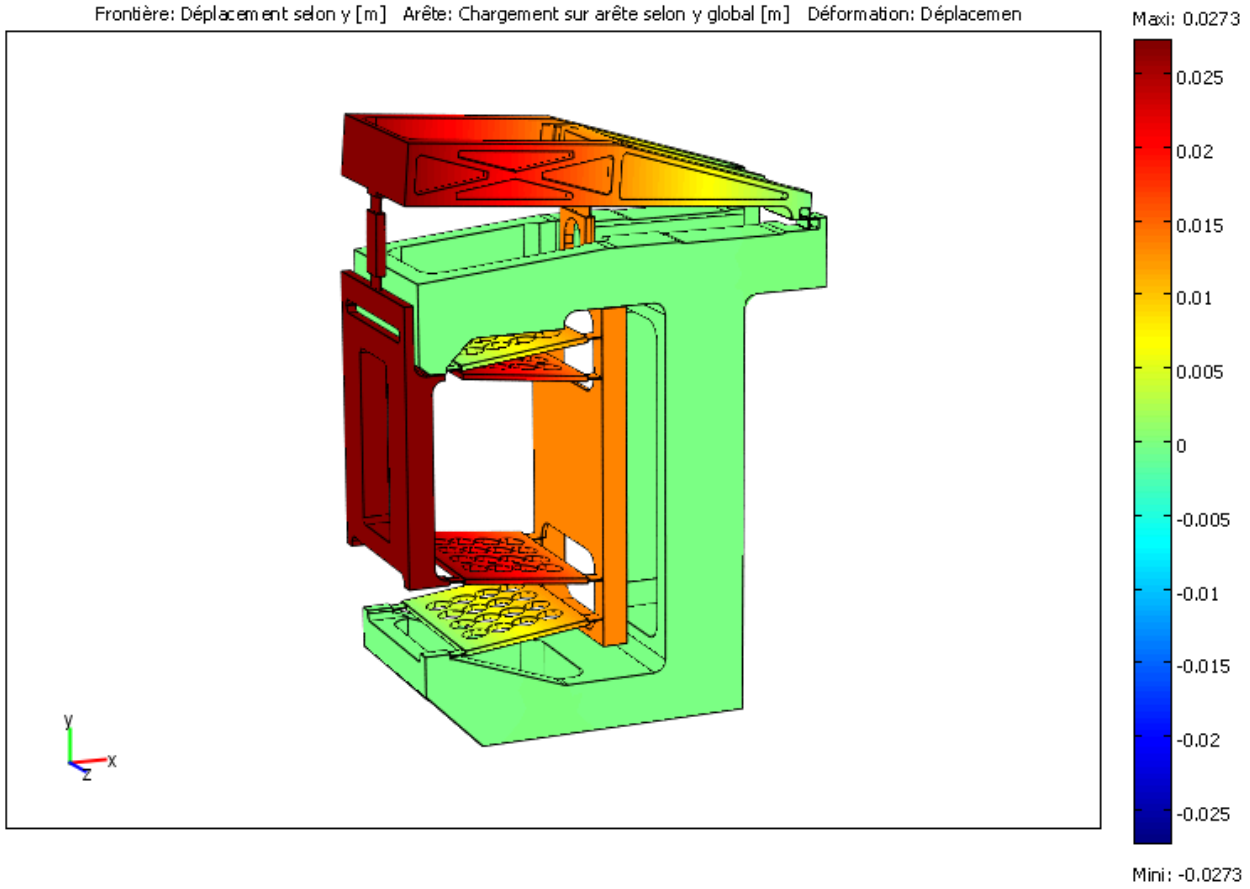
One block 445 x 370 x 140 mm^3

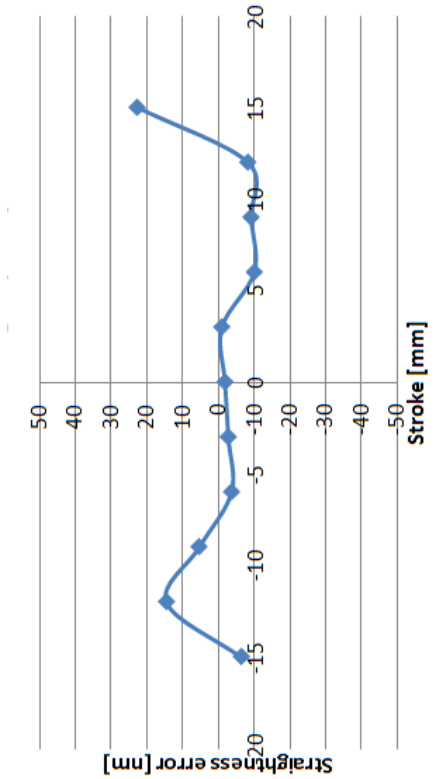
METAS

BWM II Project: Mechanical system

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- 13-hinge stage: principle

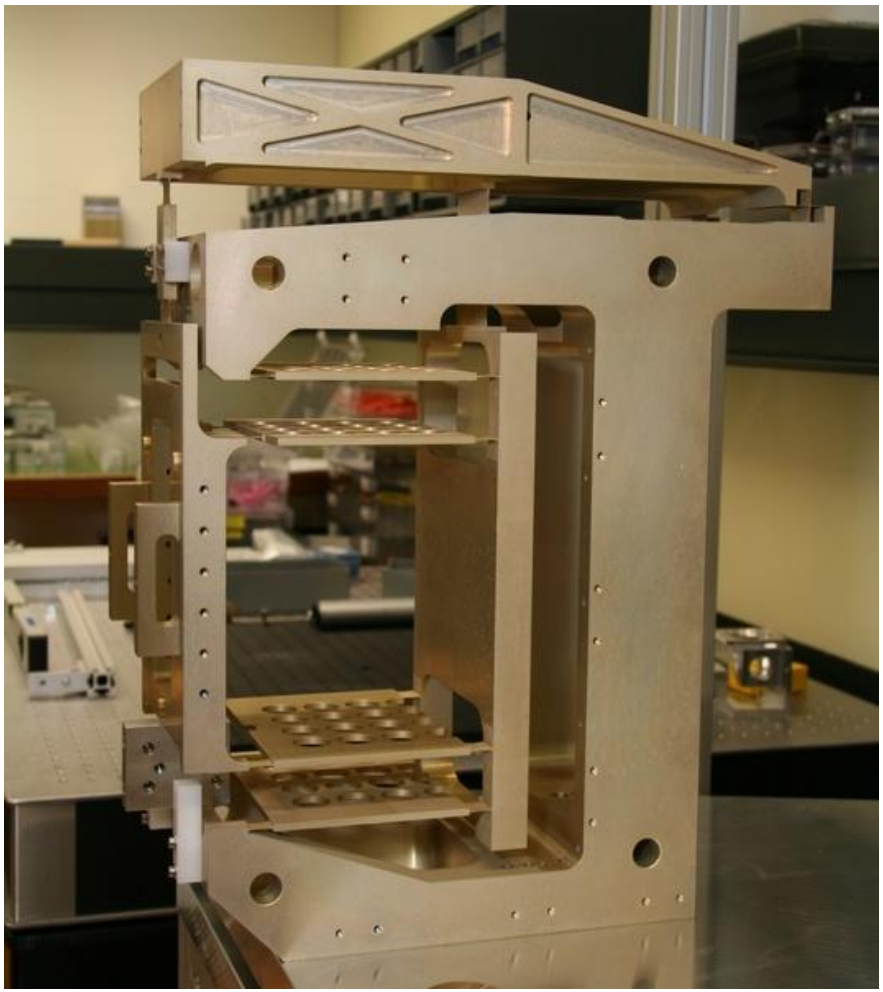


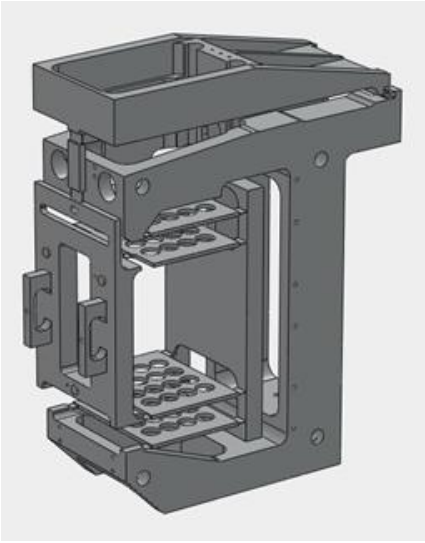


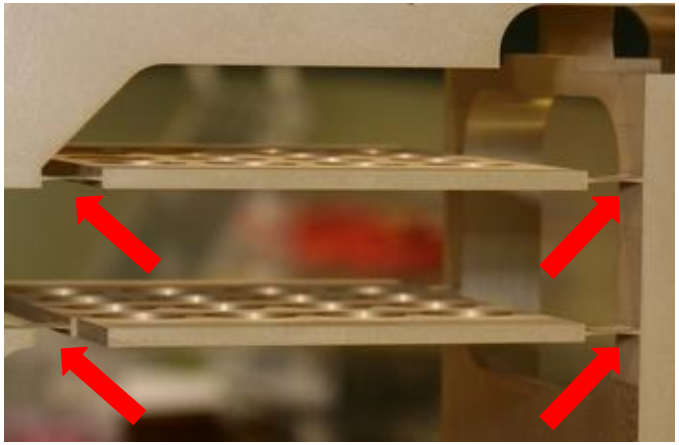
BWM II Project: Mechanical system

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- 13-hinge stage
  - 1st prototype at METAS !







155 µm

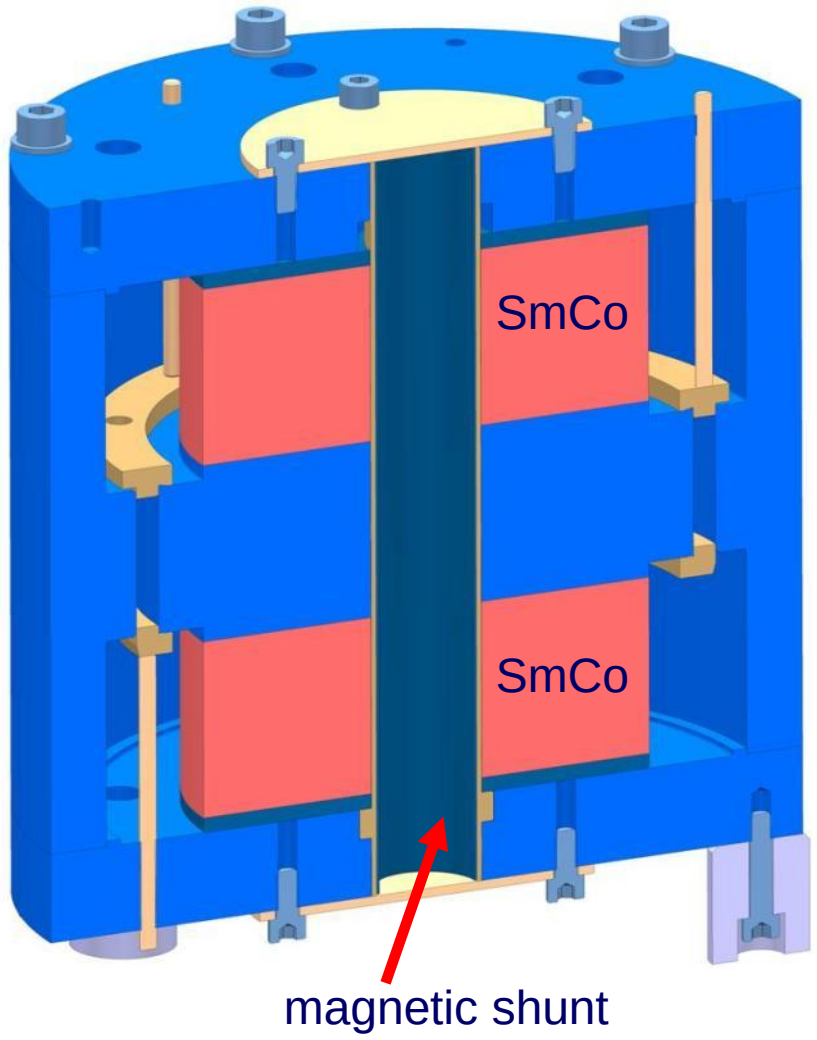
METAS

Magnetic circuit

- Cylindrical geometry (closed)
- Coil diameter: 200 mm
- Field: 0.5 T
- Compensation for thermal dependence

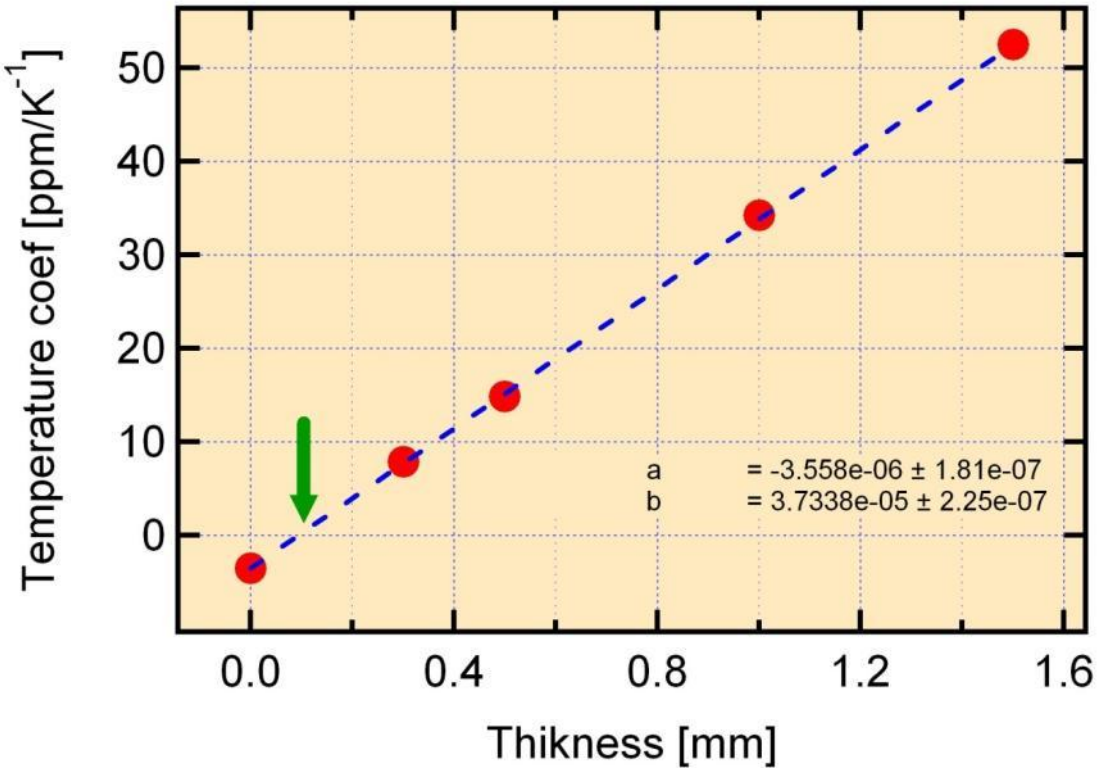
  T_m < 1 ppm/K !

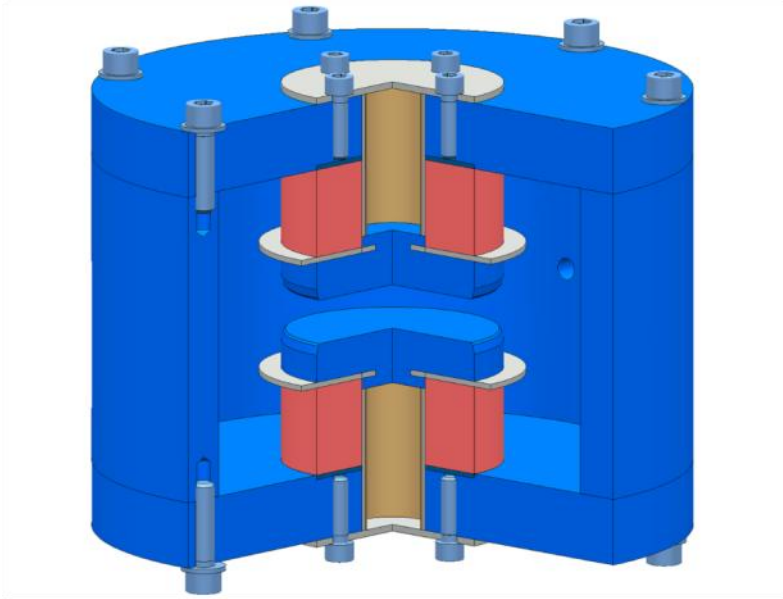
  (regular SmCo: ~360 ppm/K)

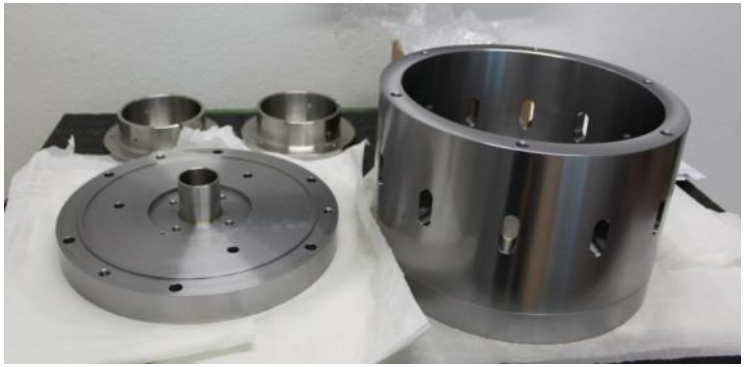


BWM II Project: New magnet

- Temperature compensation

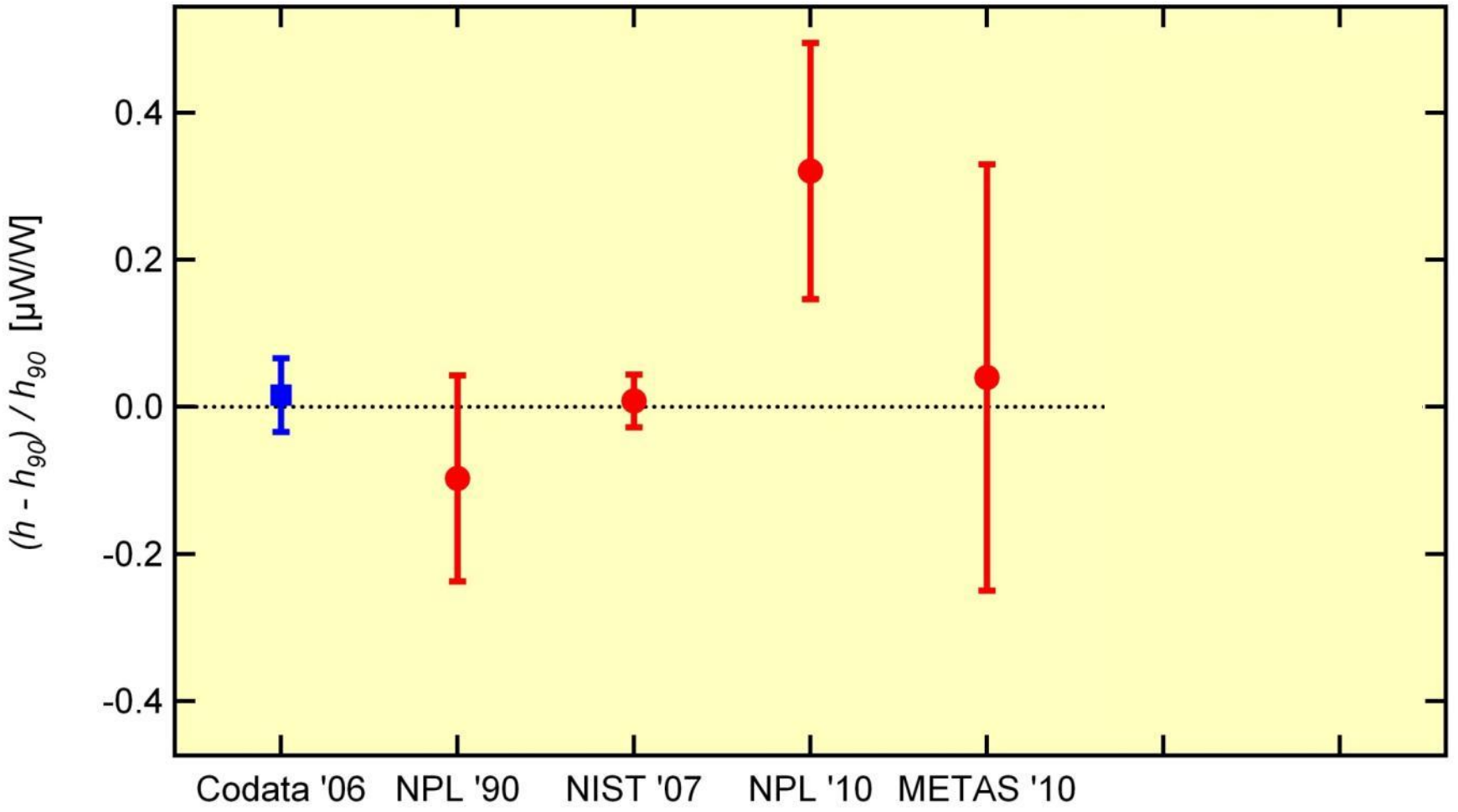






The Planck constant today

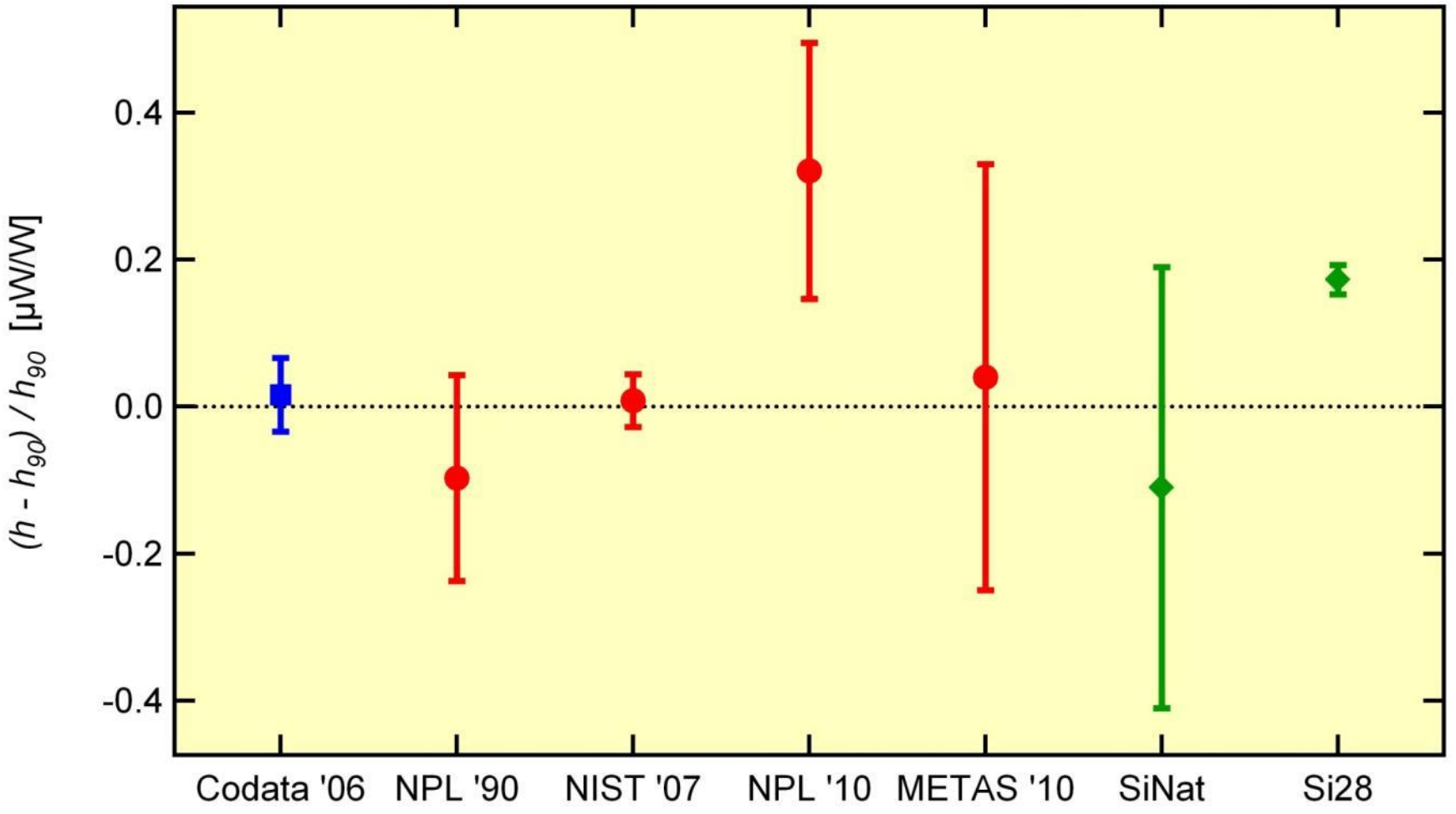
- CODATA 2006, WBs



METAS

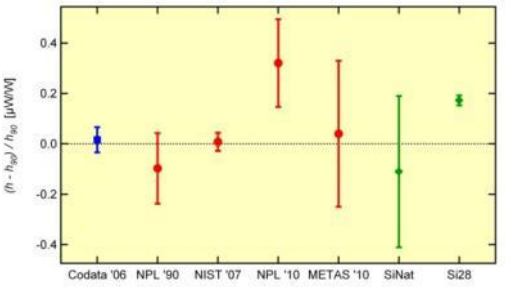
The Planck constant today

- CODATA 2006, WBs and Si



METAS

Future ?



- WBM I project is finished
- WBM II is on schedule
  - Apparatus mounted in 2012
  - Measurement should start in 2013
- New definition in 2015… ?

… it could read like this:

The kilogram, unit of mass, is such that the Planck constant is exactly $6.6260693 \cdot 10^{-34}$ Js.

Thank you for

your attention !