The NRC Watt Balance
Planck Constant Determination

Barry Wood

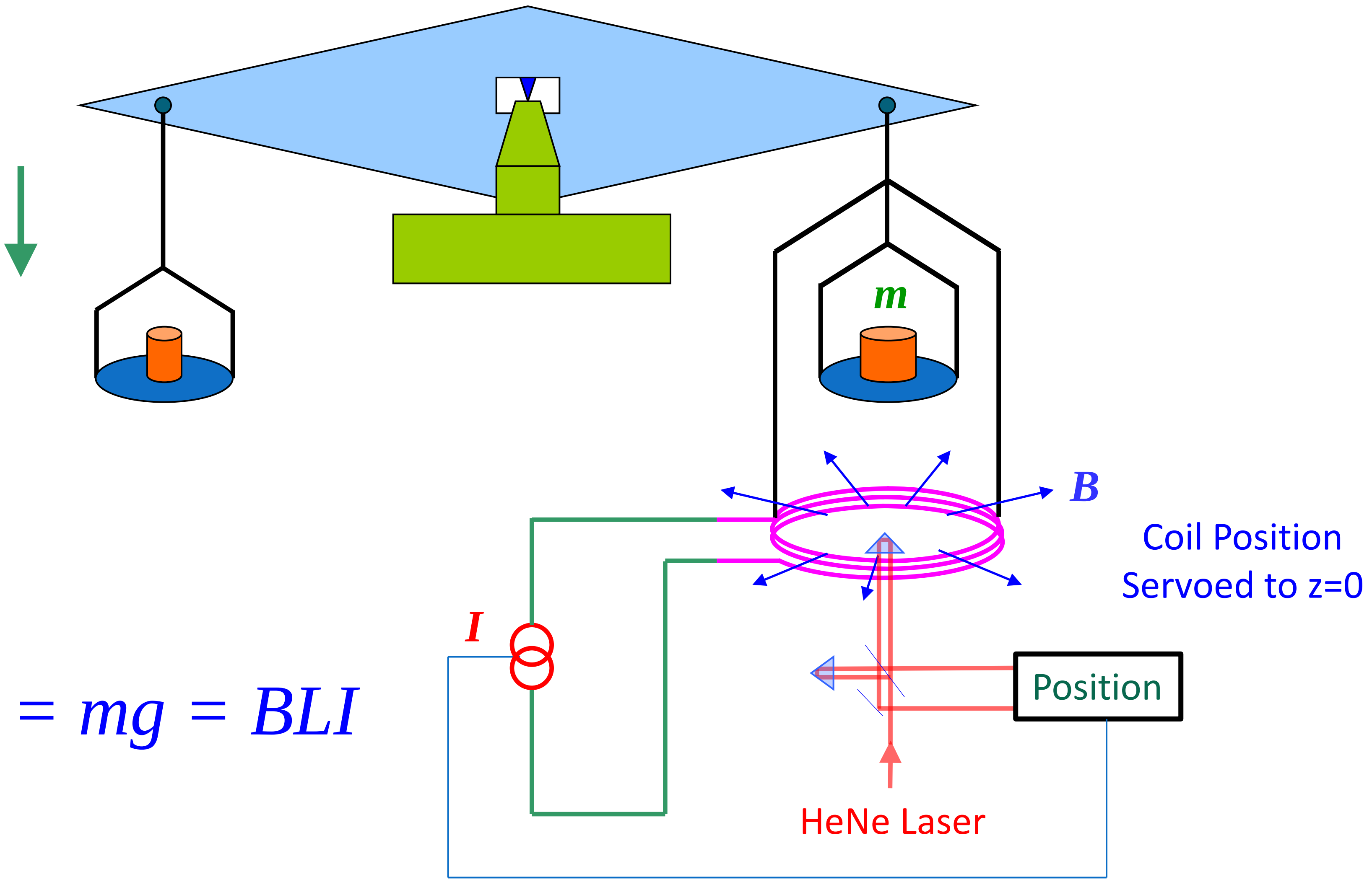
Carlos Sanchez

FC 2015
Eltville, Germany
February 4, 2015

Outline

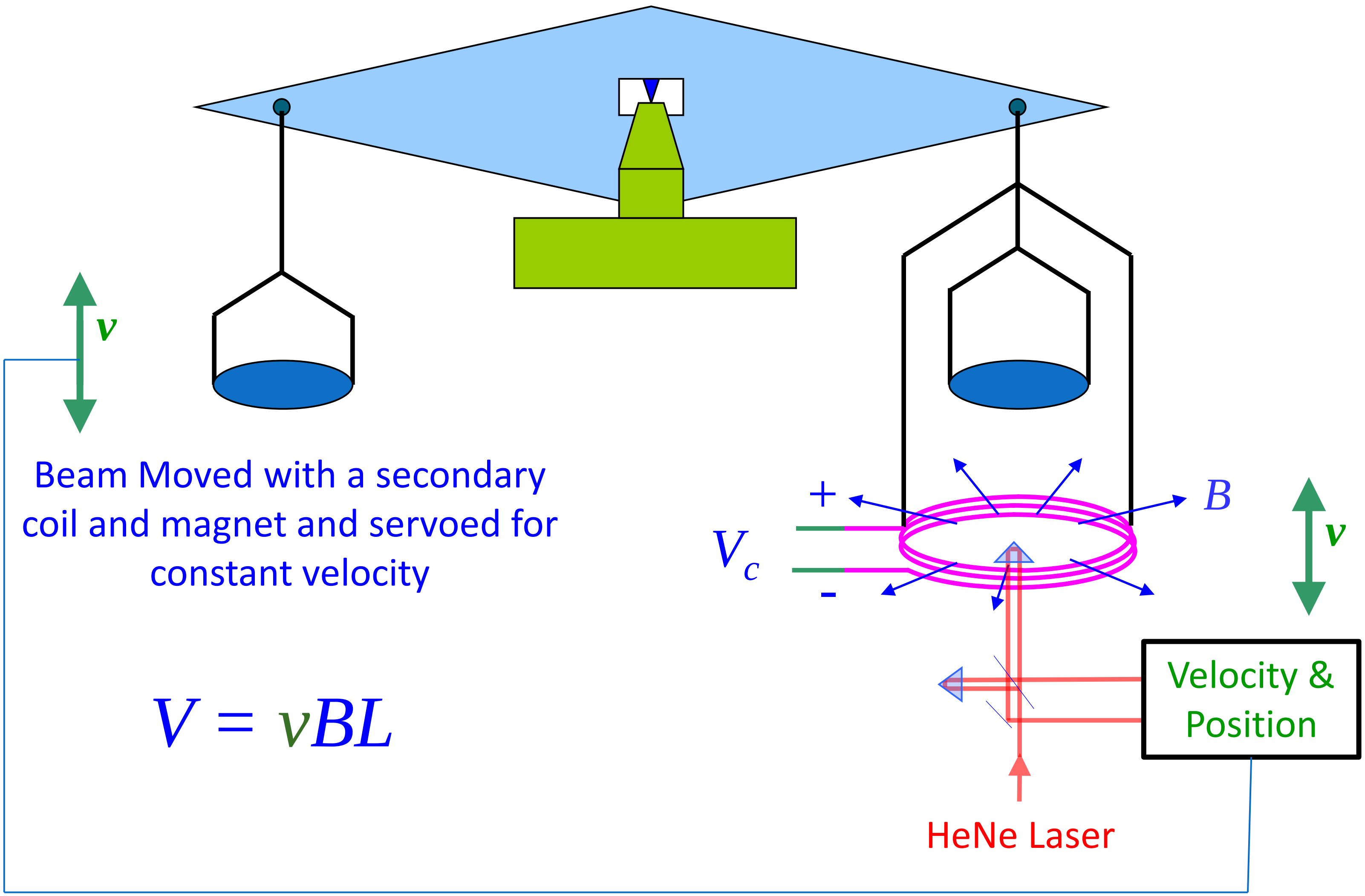
- Principles
- Underlying Measurements and Uncertainties
- Results
- Recent Corrections

Principle – weighing phase



$$F = mg = BLI$$

Principle – moving phase



$$V = vBL$$

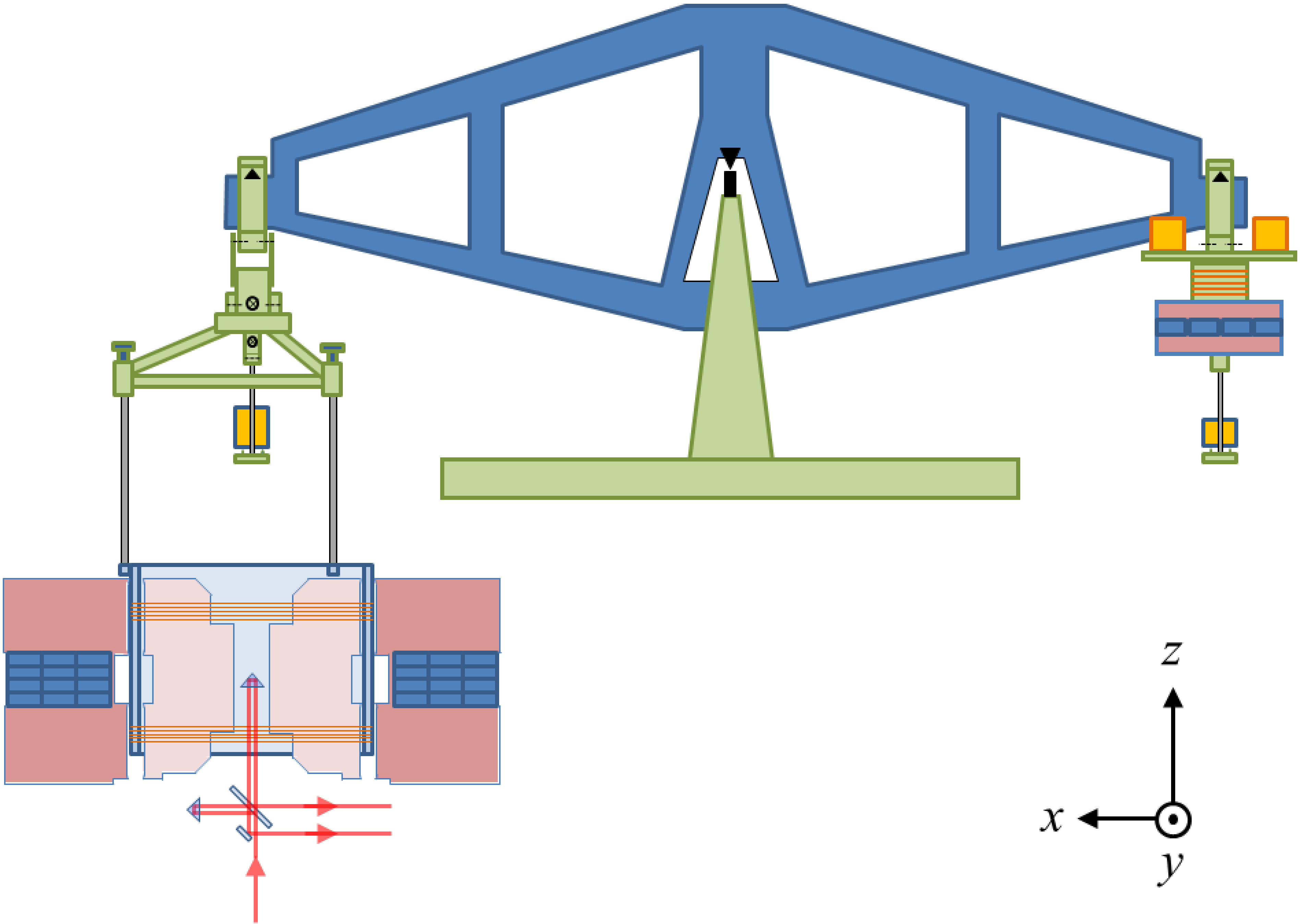
Combining both phases

Voltage $\longrightarrow$ $K_{J-90} = 483597.9\ \text{GHz/V}$

Resistance $\longrightarrow$ $R_{K-90} = 25812.807\ \Omega$

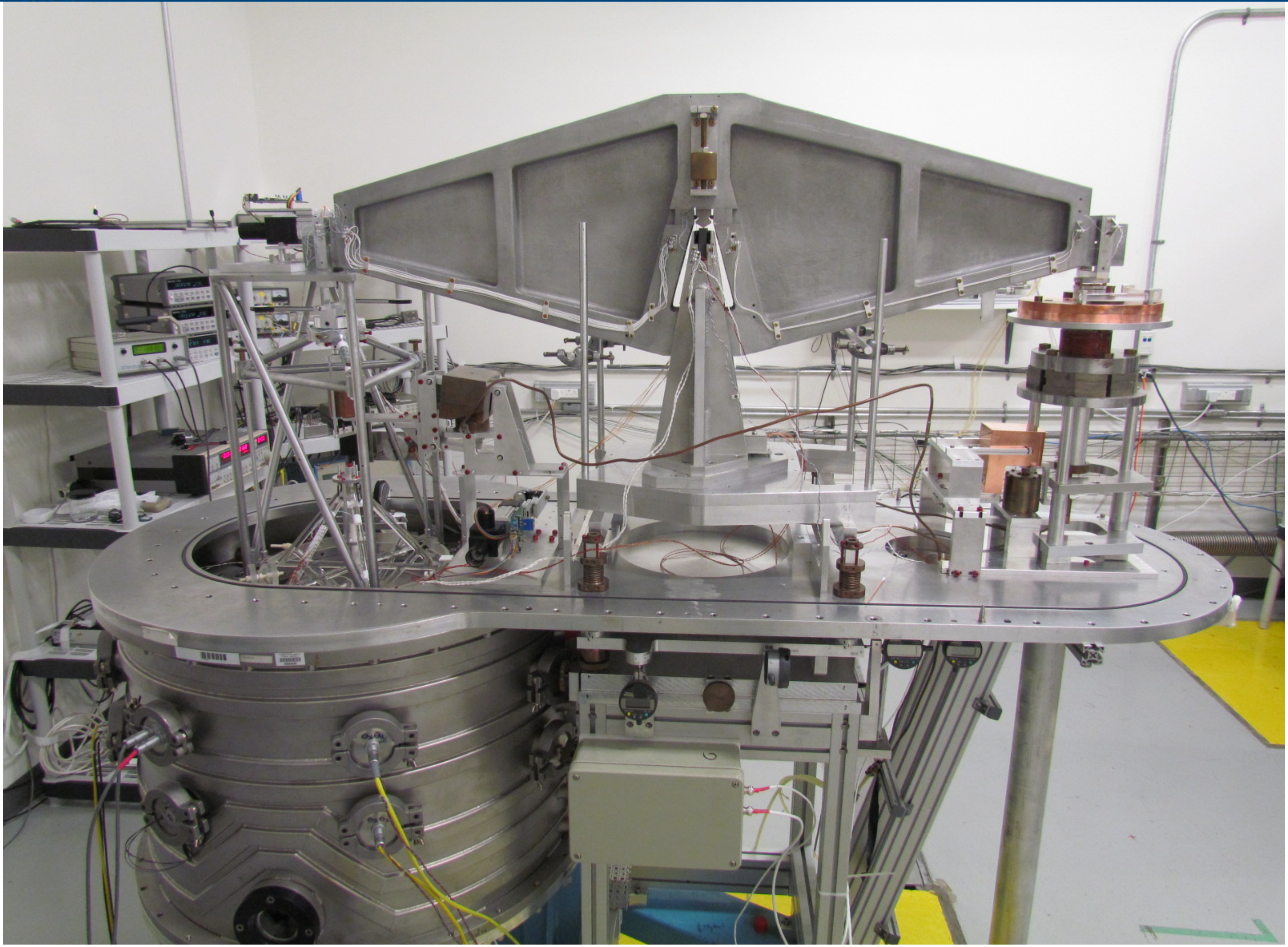
$$h = \frac{mgv}{VI} \times \frac{4}{K_{J-90}^2 R_{K-90}}$$

$$h = \frac{mgv}{VI} \times h_{90}$$


z
x
y

The NRC watt balance

NRC·CNRC



The NRC watt balance Subsections

NRC·CNRC

Control

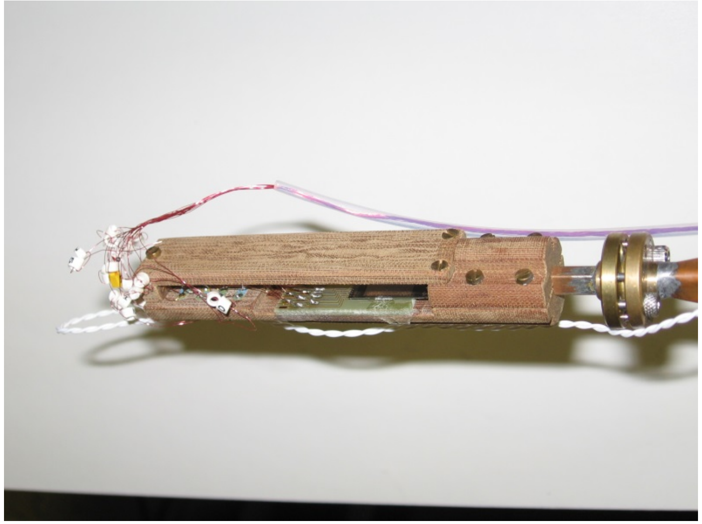
Beam control – position, velocity, acceleration, limits
Mass control – raising and lowering mass and tare
Temperature control, vibration isolation, electrical isolation, vacuum, heat flow …

Measurement

Voltage
Resistance,
Velocity and position and synchronization
Mass
Gravity
Alignment

Voltage

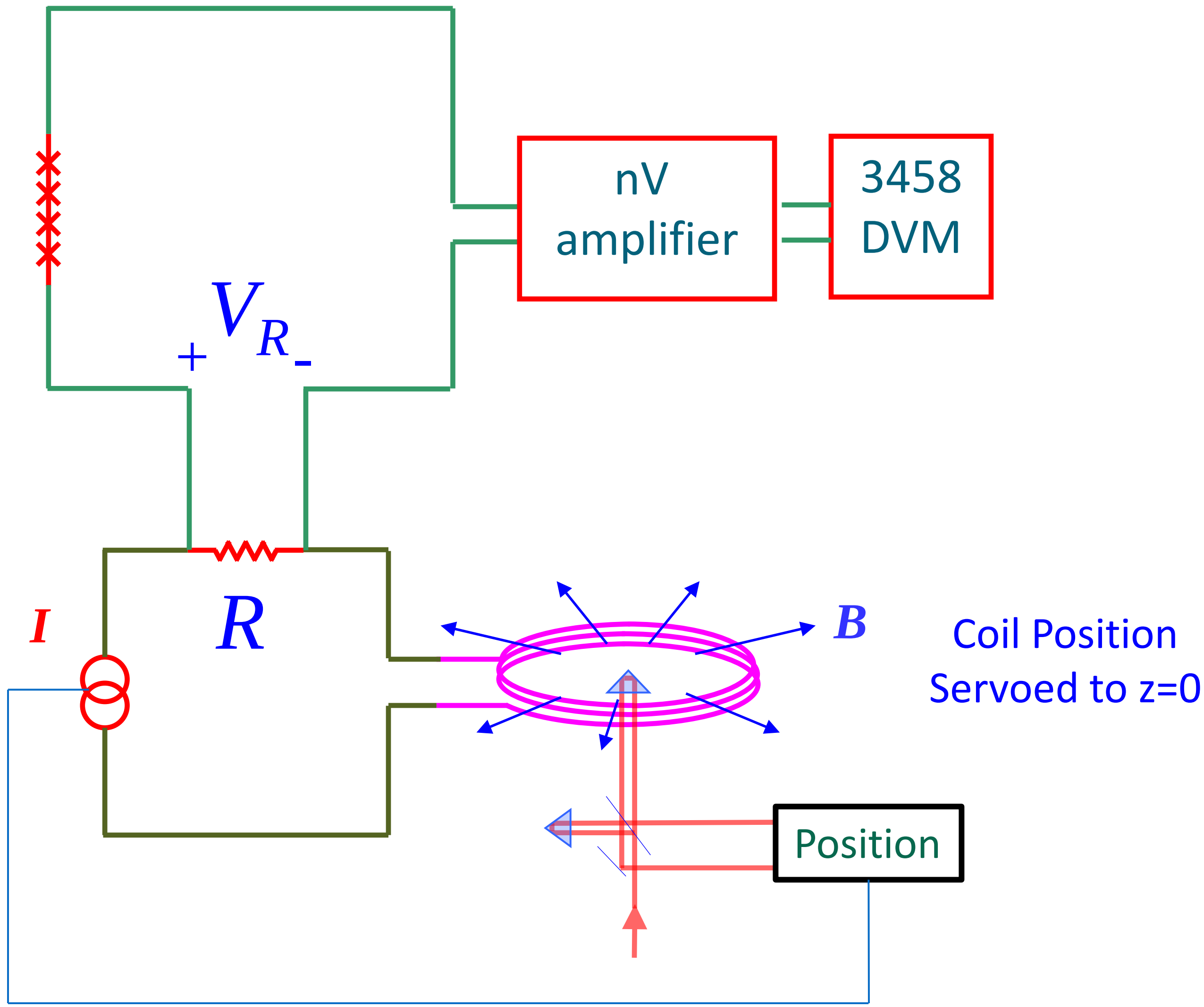
NRC·CNRC



PJVS array supplied by PTB

Voltage – weighing phase

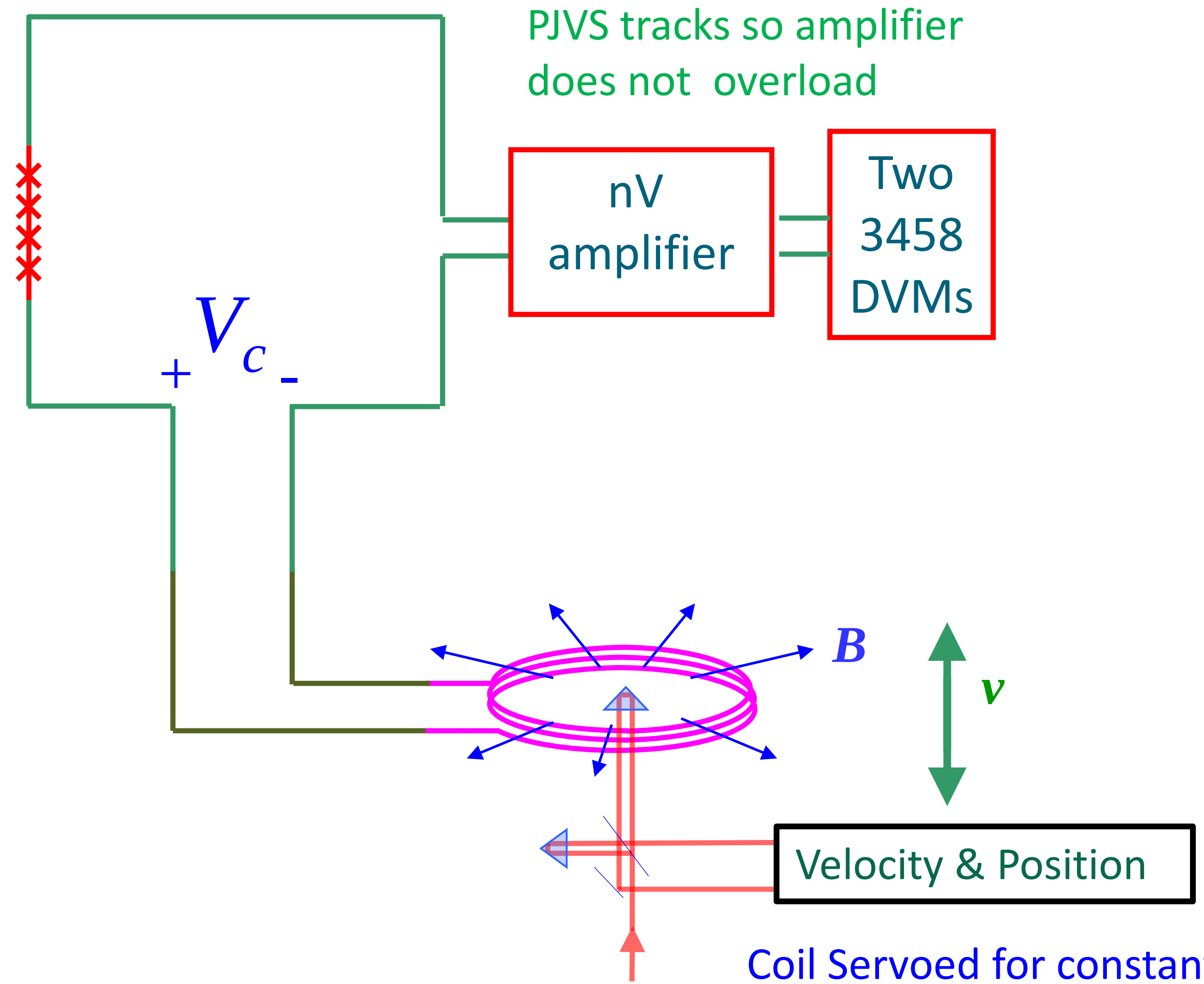
Programmable Josephson array



Raising or Lowering the mass causes the coil current to reverse

Voltage – moving phase

Programmable Josephson Array



Synchronized measurements of coil voltage and coil velocity.

Coil Servoed for constant velocity (~ 10ppm)

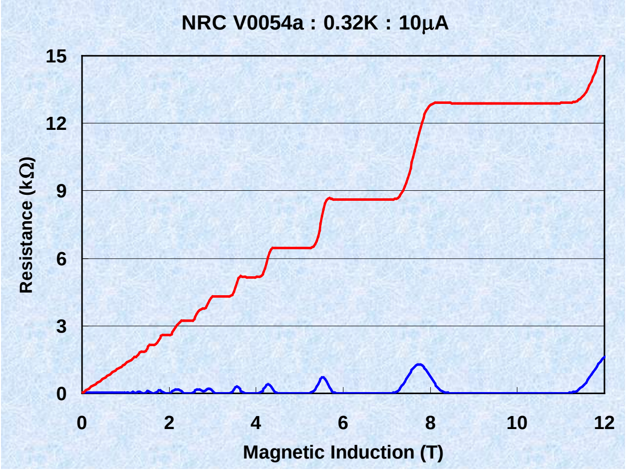
Voltage Uncertainties

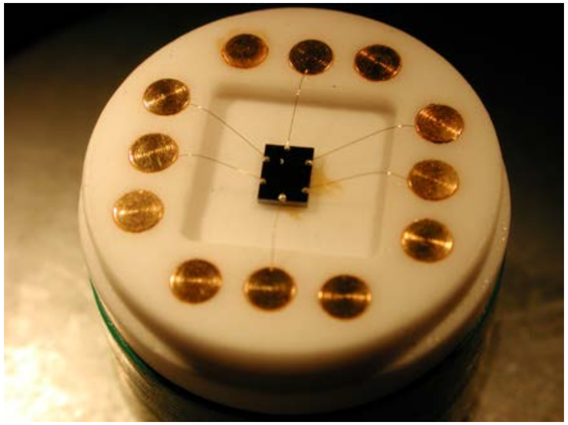
Voltage uncertainties (parts in 10^9)	
Microwave frequency	0.2
Filter leakage	< 0.1
Nanovoltmeter gain	0.3
Voltmeter non-linearity	1.6
Combined	**1.63**

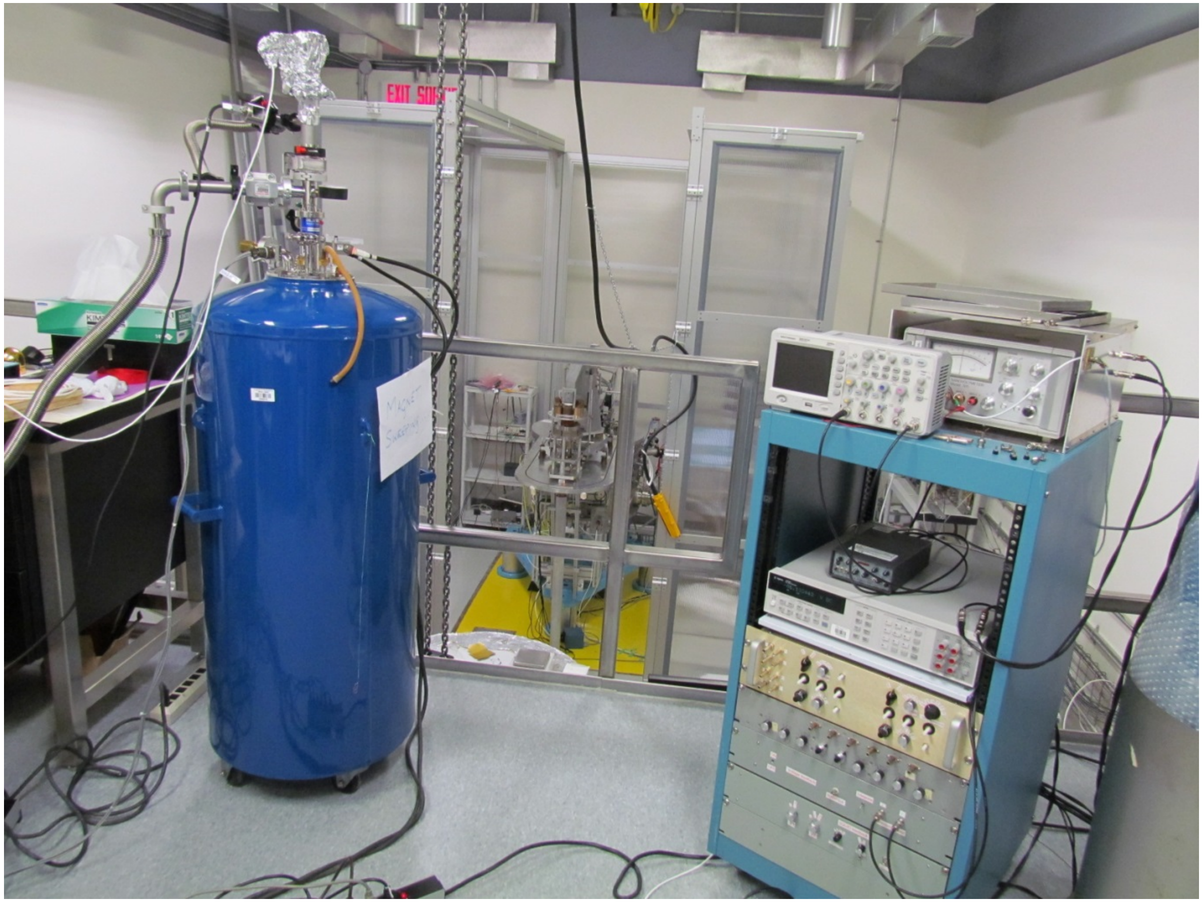
Resistance

NRC·CNRC

The watt balance 50 ohm resistors are calibrated in-situ with a portable QHR and CCC at the operating currents.





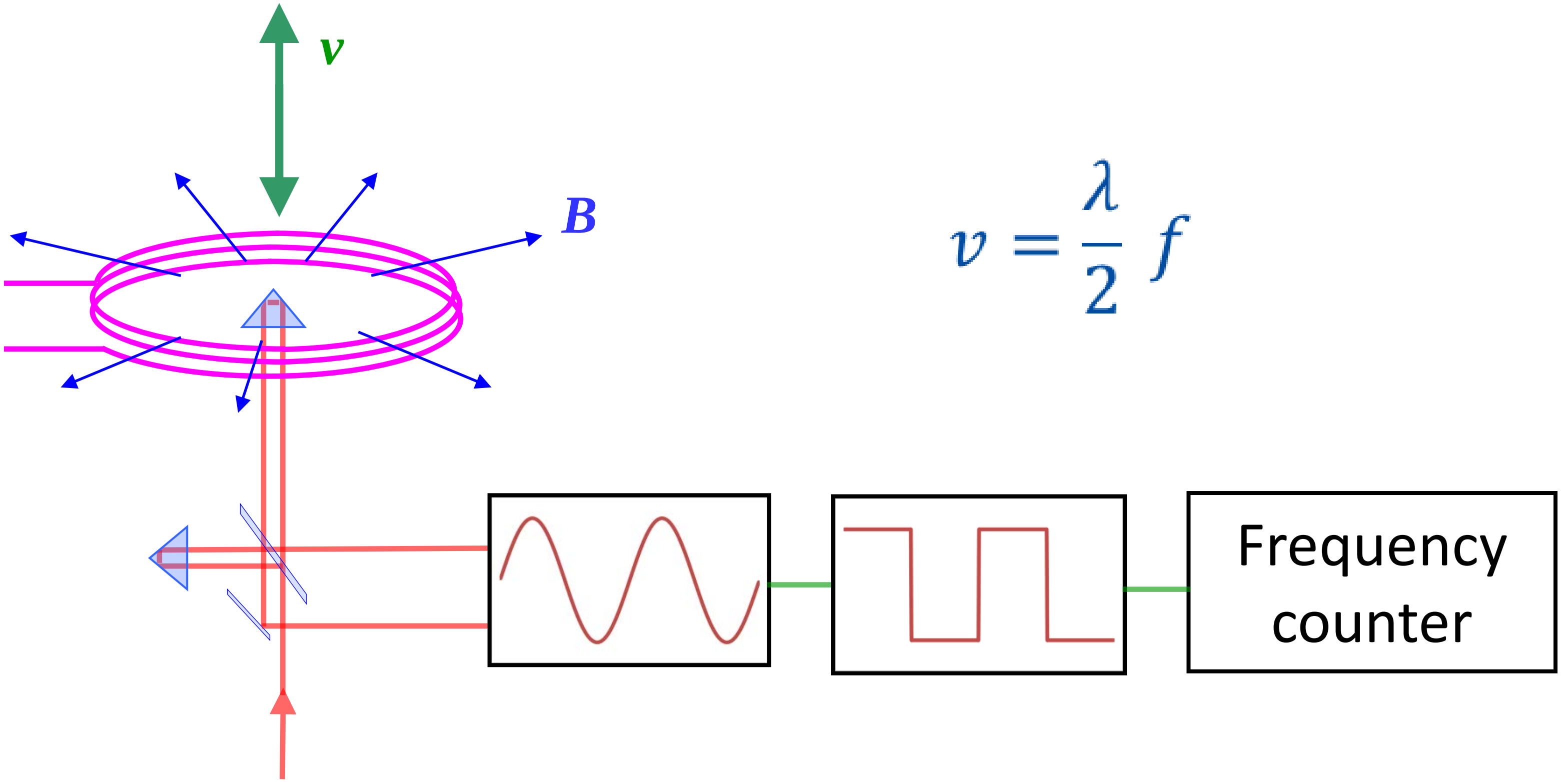


Resistance Uncertainties

Resistance uncertainties (parts in 10^9)	
Measurement vs QHR	3
Sample dissipation	3
Resistor stability	5
Resistor power coefficient (1 kg)	2

Combined	**6.9**

Velocity



$$v = \frac{\lambda}{2} f$$

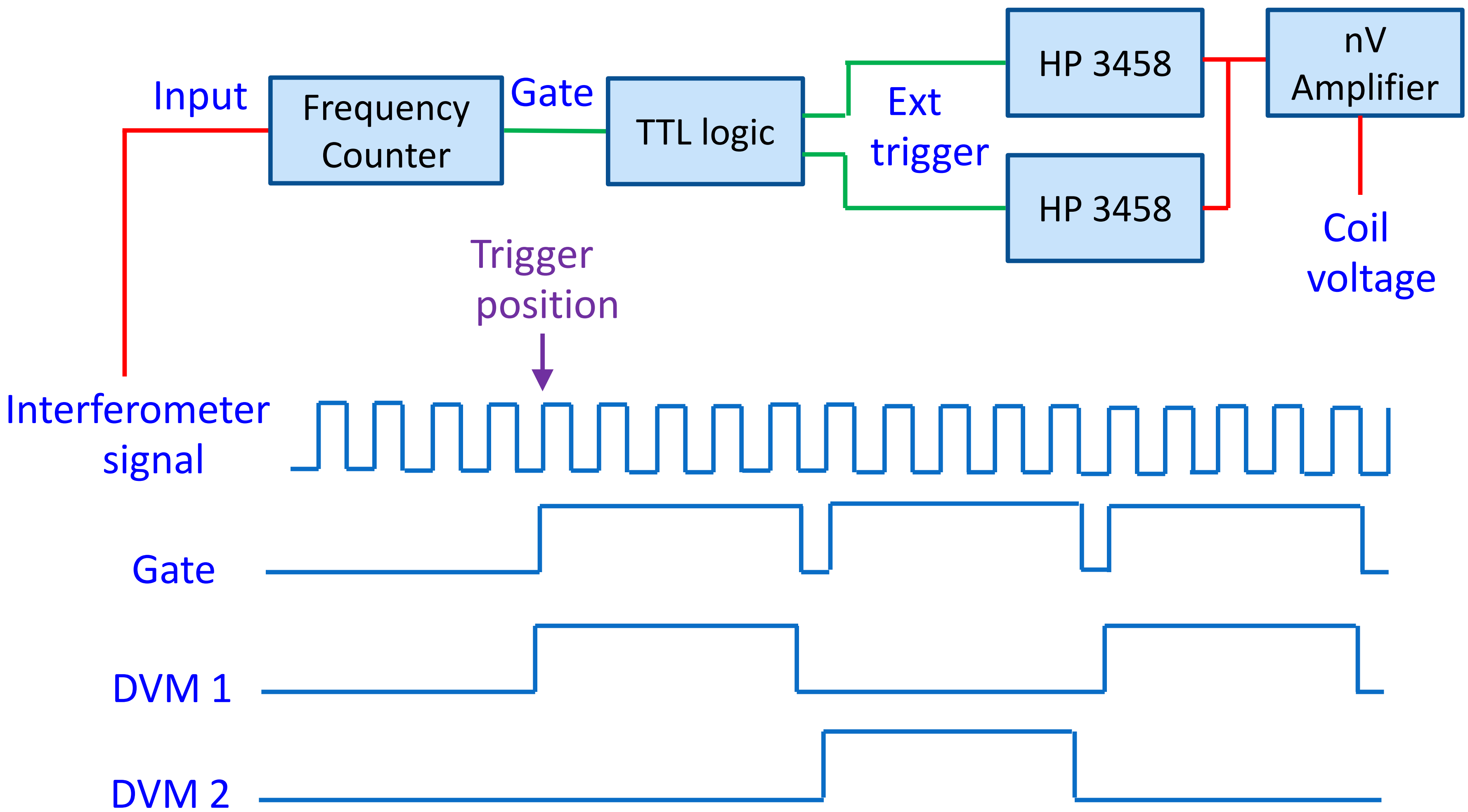
He-Ne Laser

The laser is calibrated in-situ through an optical fiber link to the NRC time and frequency lab.

Operation at constant velocity means detector rise times do not cause an error.

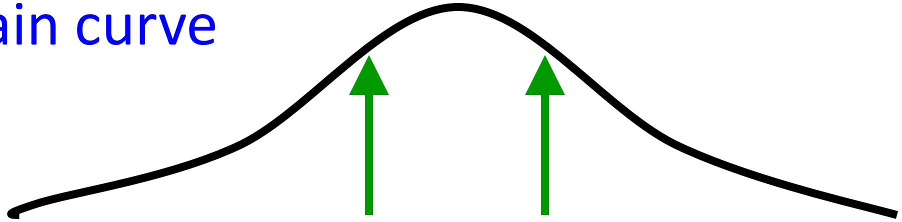
Voltage – Velocity – Position Synchronization

NRC·CNRC



Polarization leakage

He – Ne gain curve



Error caused by second mode leaking into the interferometer

Old laser – polarization stabilized

Δf = 640 MHz $\quad \dfrac{\Delta f}{f} \approx 1\times10^{-6}$

New laser – transverse Zeeman stabilized

Δf = 0.5 MHz $\quad \dfrac{\Delta f}{f} \approx 1\times10^{-9}$

Velocity Uncertainties

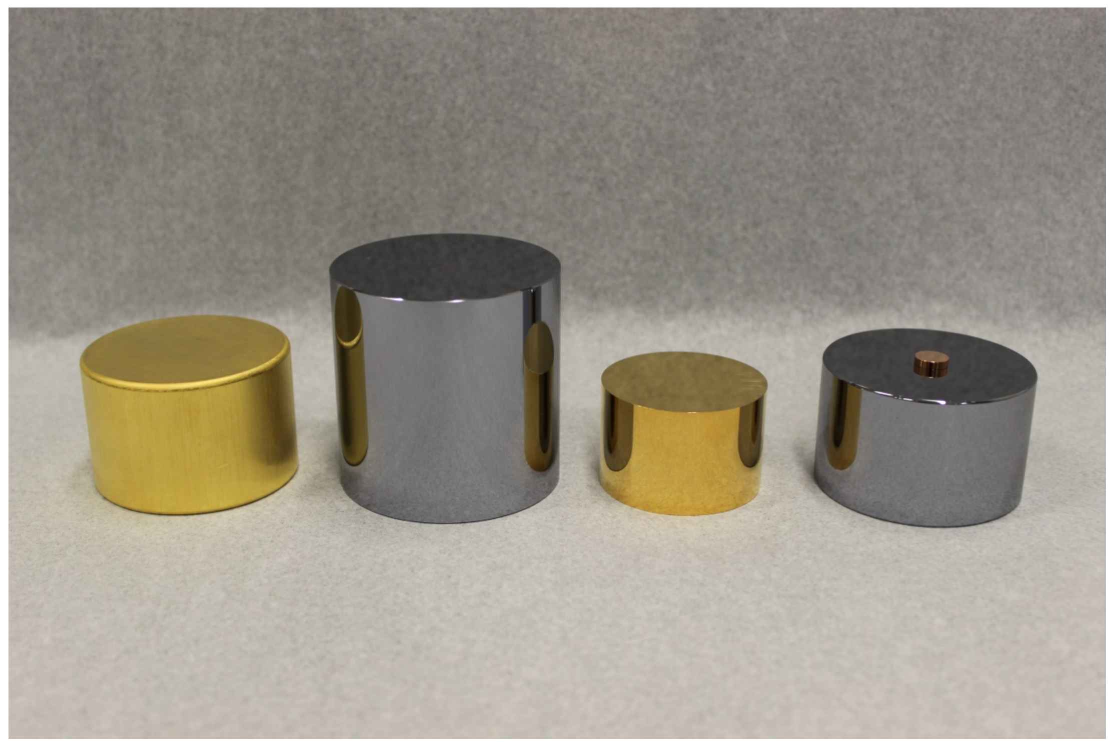
Velocity uncertainties (parts in 10^9)	
Laser wavelength	0.8
Mode leakage	< 0.1
Diffraction correction	0.2
Retroreflector imperfections	0.2
Beam shear	0.3
Frequency measurement	0.1
Index of refraction correction	0.1
Synchronization	< 0.1
Position error	0.9

Combined	**1.3**

Mass

NRC M-one vacuum mass comparator

- Pt-Ir mass calibrated at BIPM
- Vacuum-Air difference evaluated
- Test masses measured in vacuum

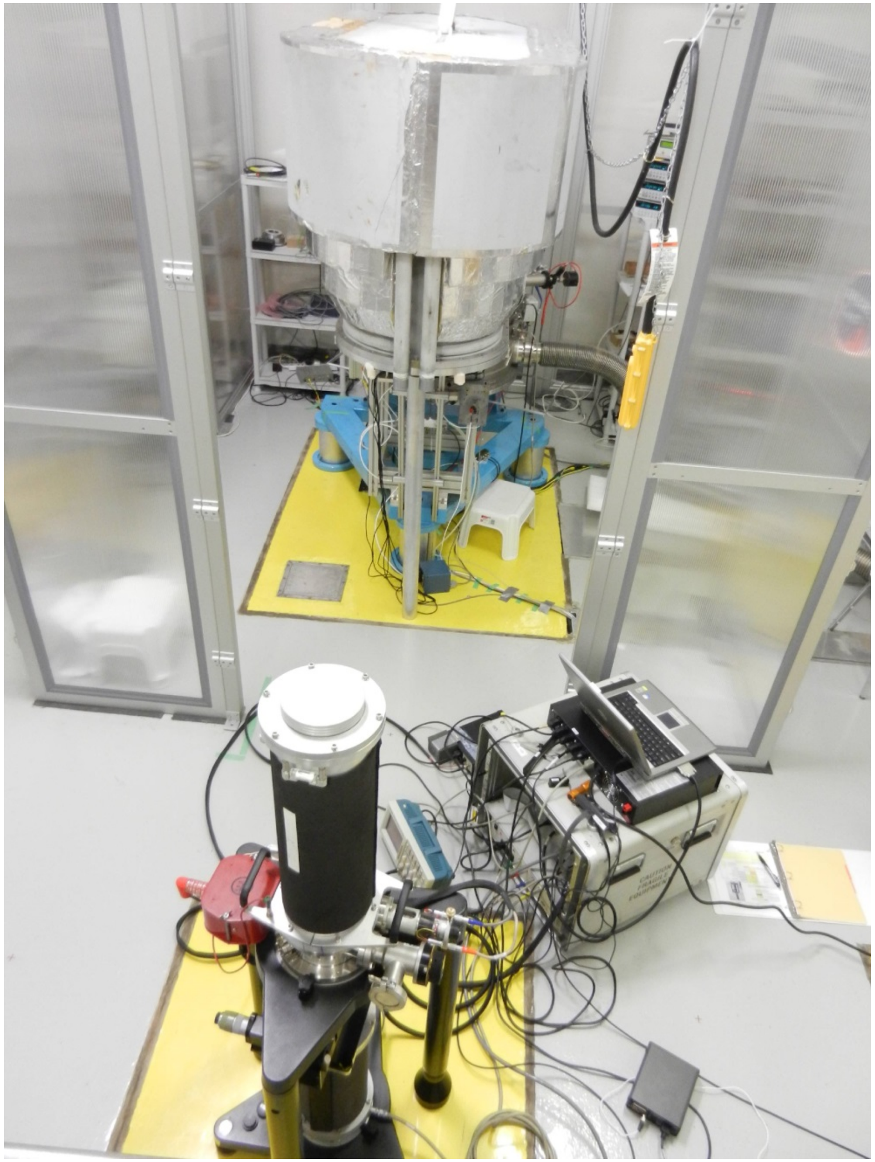


Mass Uncertainties

NRC·CNRC

Mass uncertainties for 1 kg (parts in 10^9)	
BIPM calibration uncertainty	7.2
Transport stability	3.5
Balance uncertainties	2
Stability of reference mass	2.8
Pressure dependence	1
Corrections	
Sorption on reference	2
Center of gravity	< 0.1
Weighing range sensitivity	0.2
Combined	**9.0**

Gravity



- Three isolated gravity pads.
- 3D Mapping of variations within lab
- Modeling of variations with balance in place
- Tide program, polar motion…
- Seasonal variations ~ 3ppb
- Gravity re-measured in July 2013 and Jan 2014
- Gravimeter compared with NIST and NRCan with good agreement

J. Liard, C. Sanchez, B Wood, D. Inglis and R. Silliker, *Gravimetry for watt balance measurements*, *Metrologia* **51** S32–41, 2014

Gravity Uncertainties

Gravity uncertainties (parts in 10^9)	
Absolute measurement	2.7
Horizontal transfer	2.5
Vertical transfer	3
Corrections	
Balance attraction	1
Earth tide	< 0.1
Polar motion	0.1
Ocean loading	0.3
Atmospheric pressure	0.3
Seasonal changes	3
Combined	**5.7**

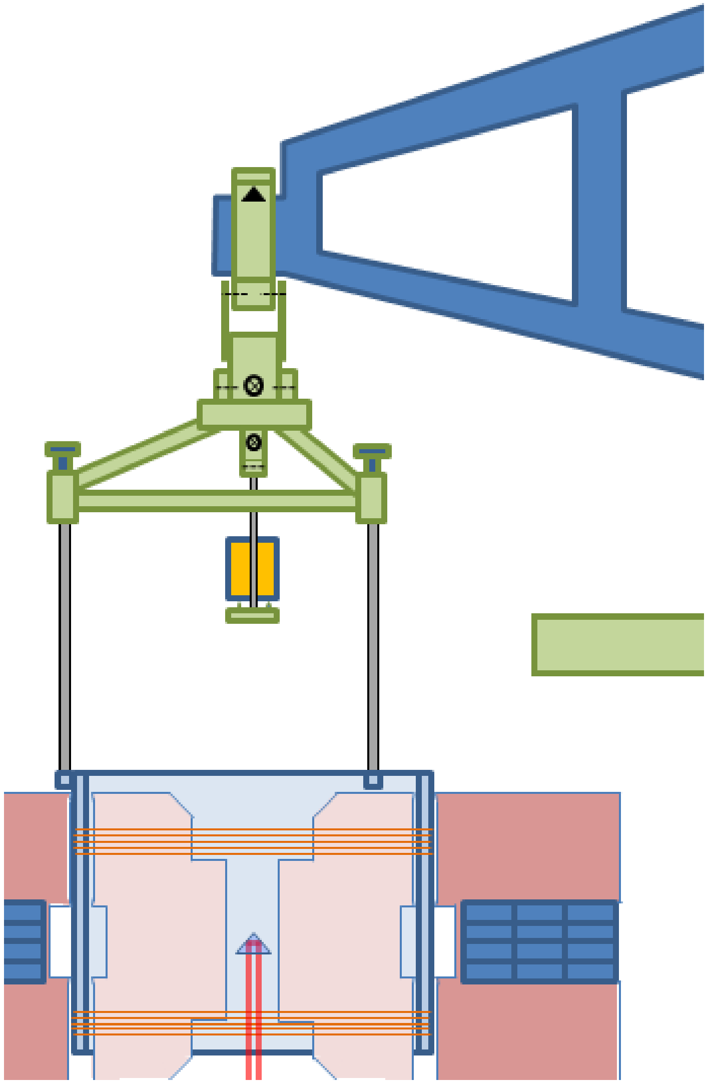
Alignment

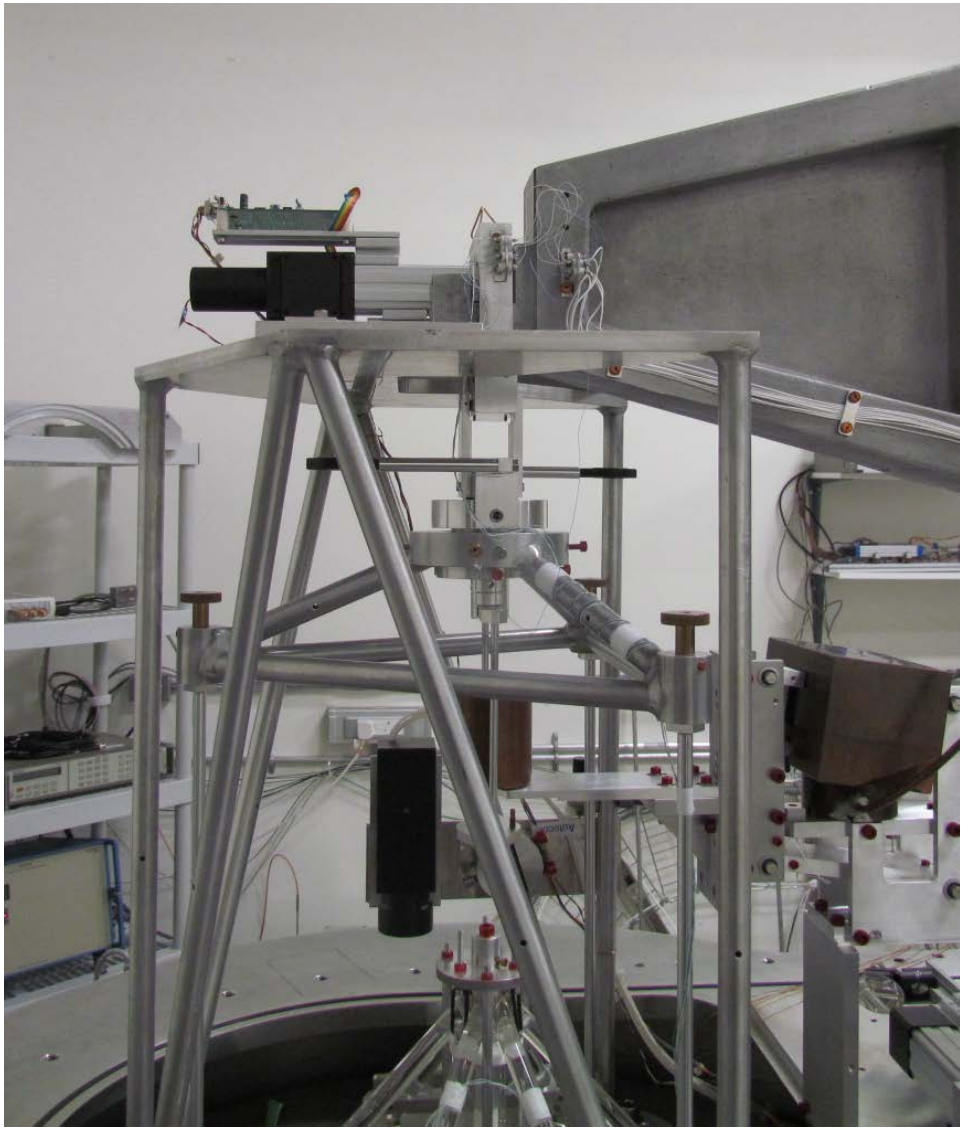
- Horizontal forces: F_x , $F_y \approx 0$
- Horizontal velocities: v_x , $v_y \approx 0$
- Torques: τ_x , τ_y , $\tau_z \approx 0$
- Angular velocities: ω_x , ω_y , $\omega_z \approx 0$.
- Optical alignment (laser beam vertical, Abbe offset)
- Mass pan position

All alignment related quantities are measured in vacuum.

C. Sanchez and B. Wood, Alignment of the NRC watt balance: considerations, uncertainties and techniques, *Metrologia* **51** S42–53

Alignment





Alignment Uncertainties

NRC·CNRC

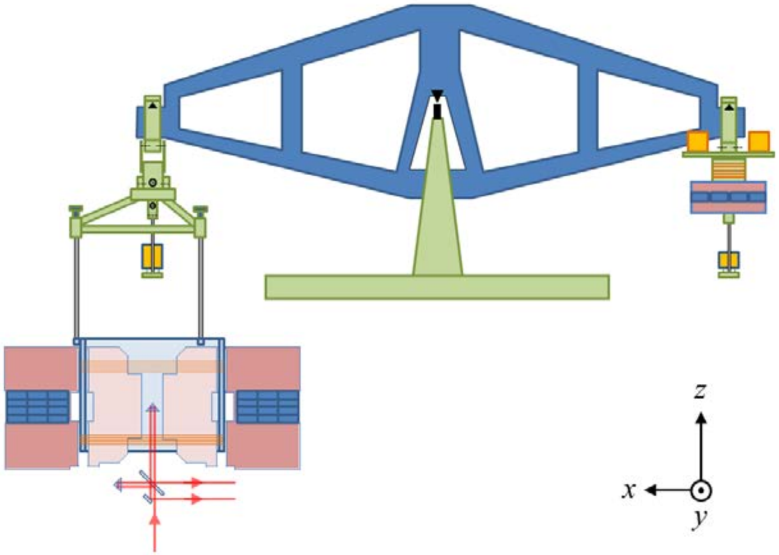
Alignment uncertainties, m_1 (x 10^{-9})	
$F_x v'_x$	0.4
$F_y v'_y$	< 0.1
$\tau_x \omega_x$	0.2
$\tau_y \omega_y$	0.7
Abbe offset correction	3.9
Mass pan alignment	0.2
Laser vertical	0.8
Horizontal displacement	2.8
Vertical displacement	2.8
Change in θ_z	1.3
Change in θ_x and θ_y	0.5

Combined	**5.9**

Systematic Effects - Mass Exchange Errors

1. Stretching of the coil support

The coil is servoed to z=0, so if the coil support stretches then beam will tilt.



Initial correction $= \left(+0.238 \pm 0.018\right) \dfrac{\mu N}{N}$

Solution

- Modification of the coil support
- Adjustment of the beam center of mass

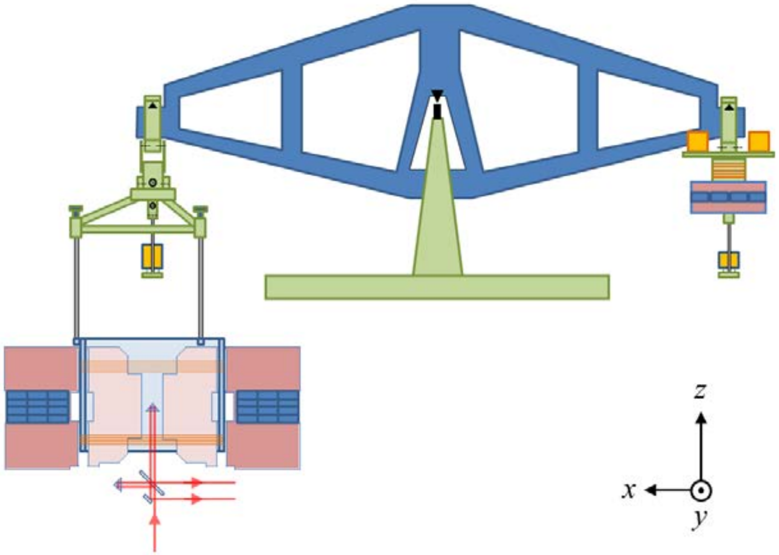
Error reduced to $< 1 \dfrac{nN}{N}$

Systematic Effects - Mass Exchange Errors

NRC·CNRC

2. Tilting of the balance base

The coil is servoed to z=0 so if the beam platform tilts the angle between the beam and the platform changes.



Initial correction $= (-0.636 \pm 0.056)\dfrac{\mu N}{N}$

Solution

- Modification of the mass lift

Error reduced to $< 1.7\,\dfrac{nN}{N}$

Other Tests for Systematic Effects

NRC·CNRC

- Change of coil position / orientation between moving and weighing phases
- Knife-edge hysteresis
- Voice coil coupling
- Dielectric absorption

These effects were found to be smaller than 3 ppb

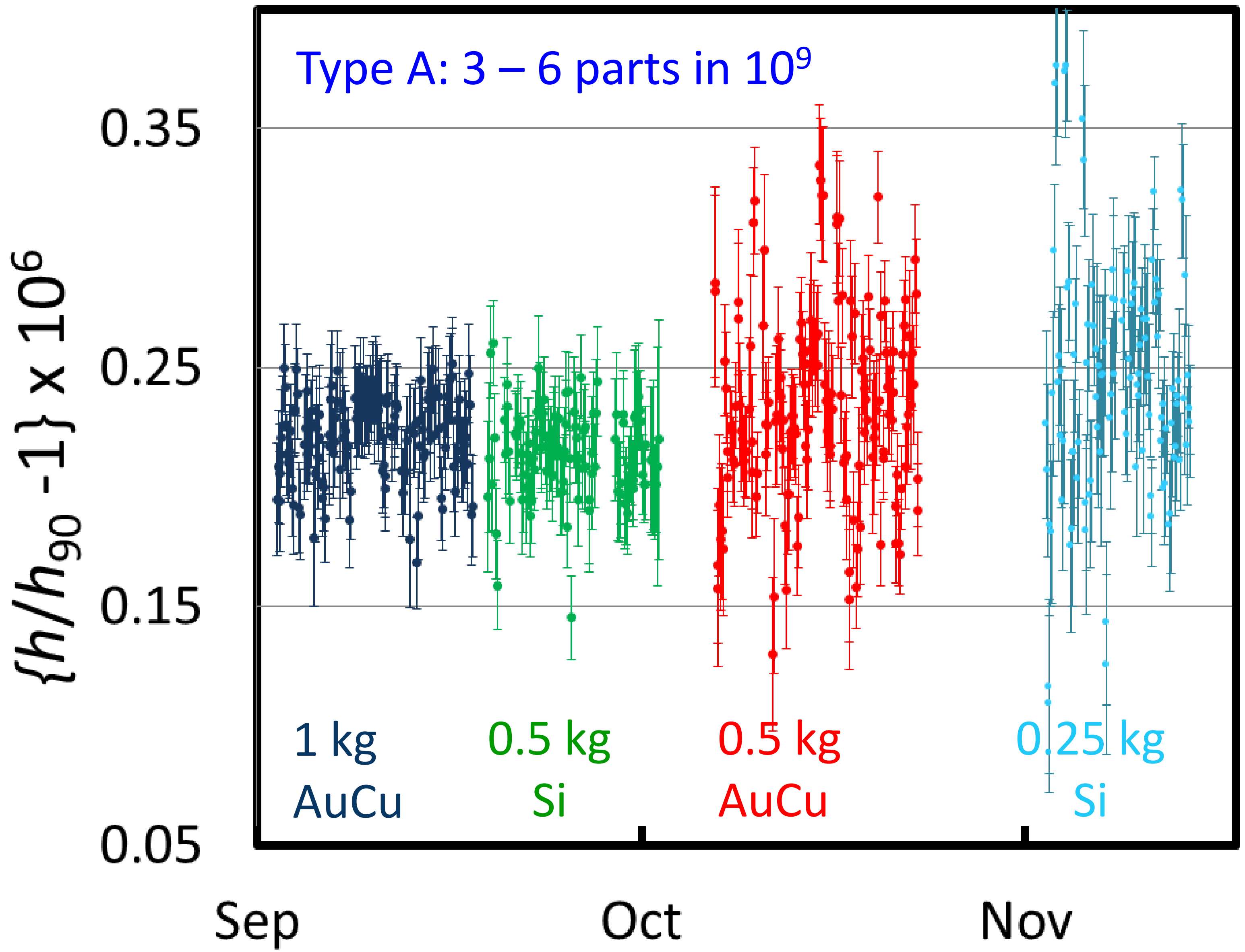
Other Uncertainties

NRC·CNRC

Miscellaneous uncertainties (parts in 10^9)	
Mass-exchange errors	1.7
Knife-edge hysteresis	1.0
Buoyancy correction	0.1
Asymmetric magnetization	0.1
Mass magnetic susceptibility	0.1

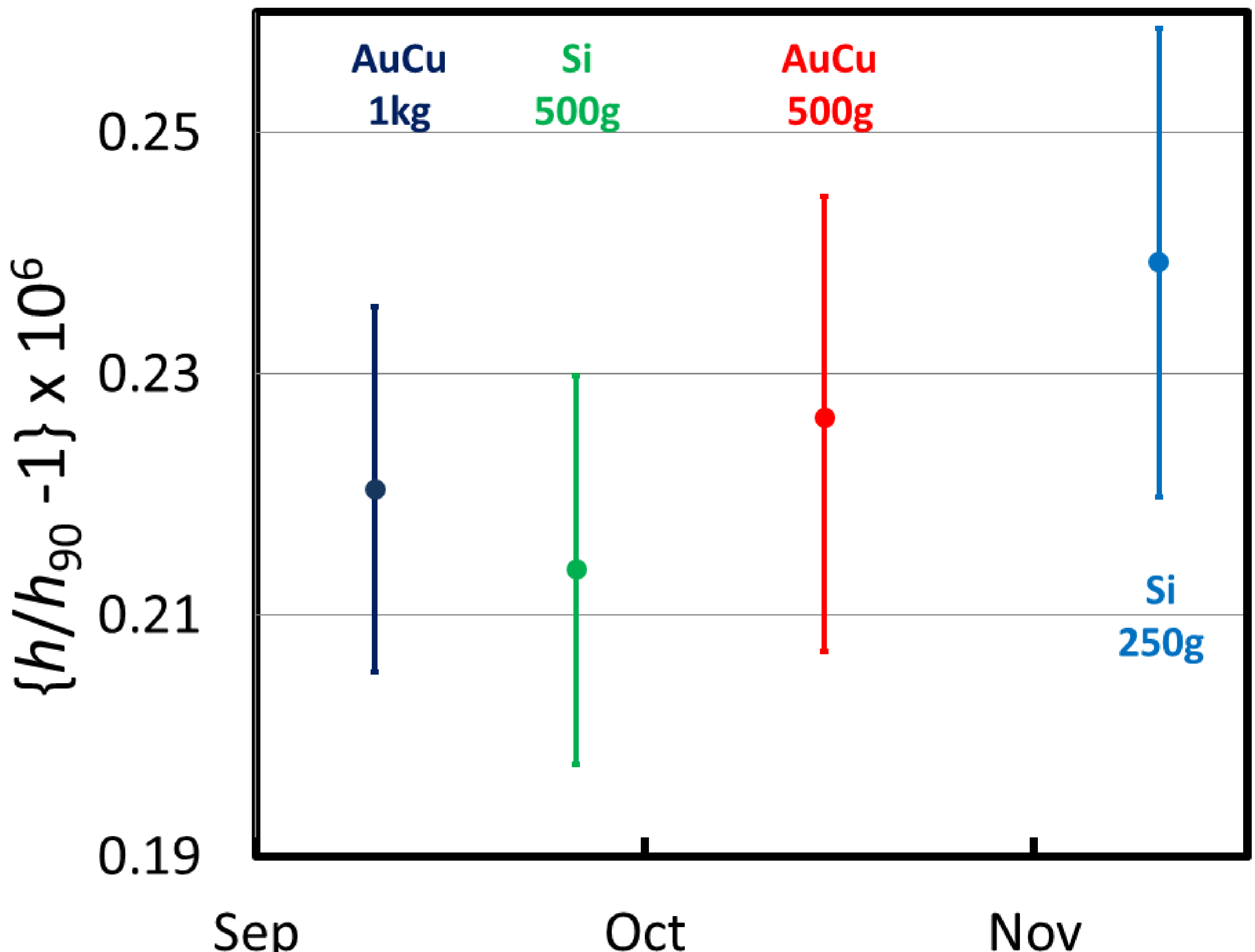
Combined	**2.0**

Original Results – All Data Points



h Results from Each Mass

NRC·CNRC



Any Other Systematic Effects ??

NRC·CNRC

Have we considered ALL systematic effects that can have a significant influence?

Apparently Not!

The IPK has only been taken out of its vault three times (1948, 1990, 2013) since it was originally stored in 1889.

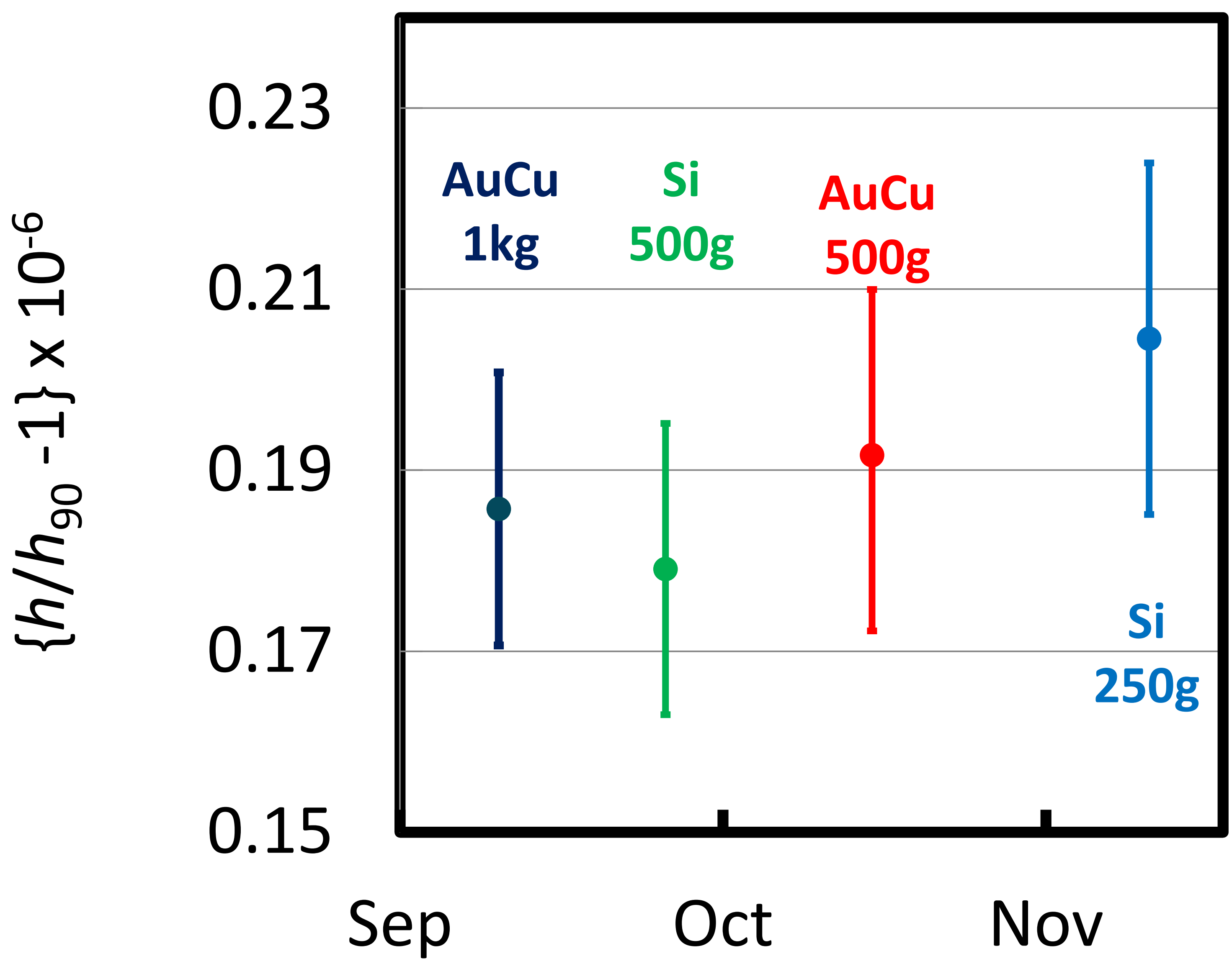
Another Systematic Effect

During the Extraordinary Calibration against the IPK conducted by the BIPM in 2014, it was discovered that the as-maintained mass unit of the BIPM has been drifting with respect to the IPK since about the year 2000.

Corrections for the mass calibrations of NRC’s mass standards were received in mid-December 2014 and they impact the NRC Planck determination of 2014.

The resulting corrections for the NRC Planck determination are 35 ppb in value and a reduction in the mass traceability uncertainty from 7.2 ppb to 3 ppb.

h Results from Each Mass – Mass Corrected



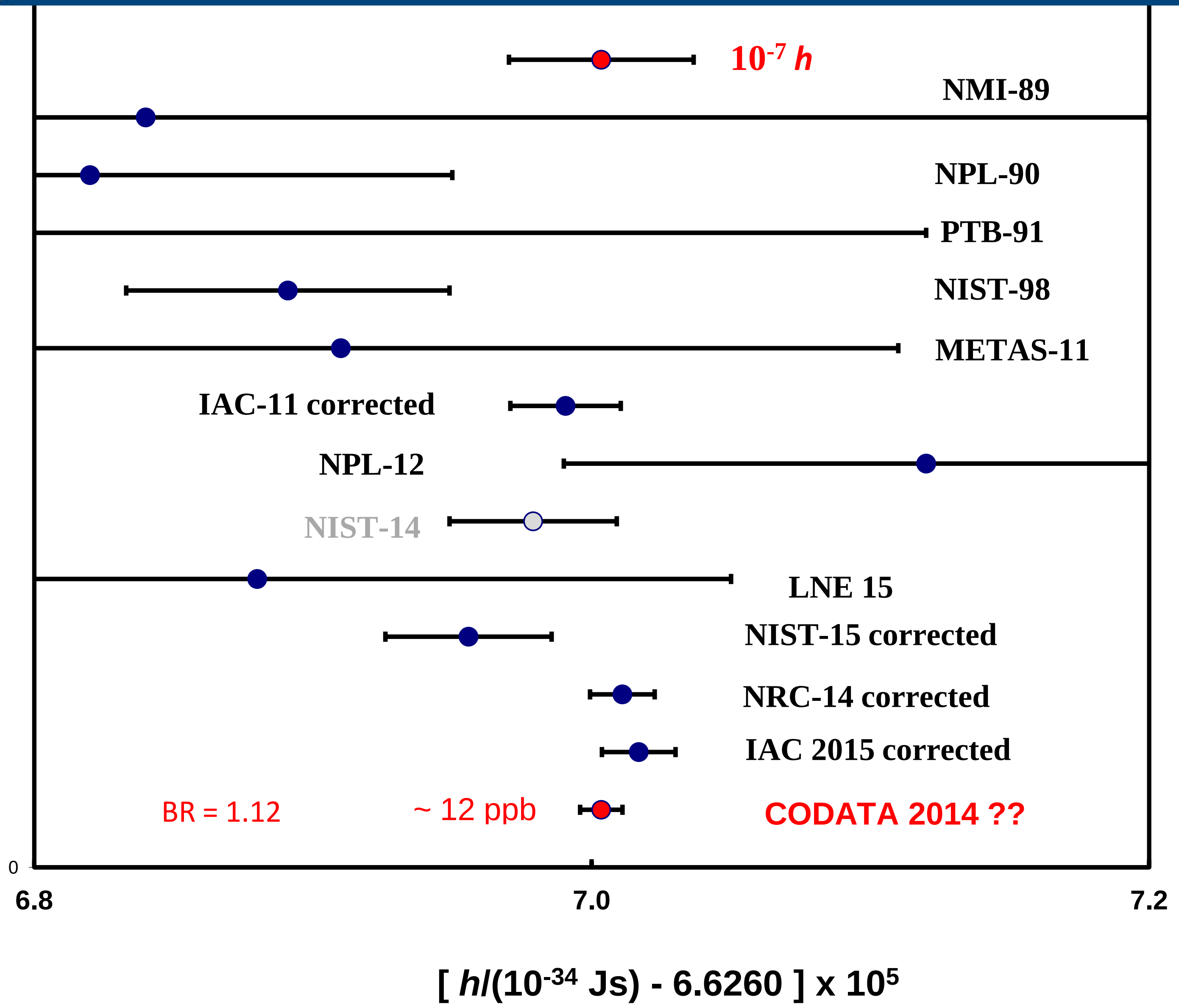
NRC Combined Result – Mass Corrected

$$\frac{h_{\mathrm{NRC\text{-}14}}}{h_{90}} - 1 = (189 \pm 18) \times 10^{9}$$

$$h_{\mathrm{NRC\text{-}14}} = 6.626\,070\,11(12) \times 10^{-34}\ \mathrm{Js}$$

Planck - February 2015

NRC·CNRC



Acknowledgements

NPL

Ian Robinson

Stuart Davidson

James Berry

PTB

Luis Palafox

Ralf Behr

NRC

Dave Inglis   Jacques Liard   Richard Green

Alan Madej   Brent Young

Thank You