A new measurement of the Planck constant using the NIST watt balance

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Arrival of the NIST-4 magnet at the non magnetic facility.
In 2011, three measurement with $\sigma_{h/h} < 100$ ppb

- Fact: Results do not agree within uncertainty.
- Desired: Numbers to be consistent within 95% confidence.
- Fact: It takes 5+ years to build a new, competitive experiment.
- Way forward: One more campaign with the existing NIST-3 apparatus.

Blind Measurement:

\[
\text{Adjusted Mass} = \text{True Mass} \times (1 + \text{R})
\]

The constant R is a number between $-500 \times 10^{-9}$ and $+500 \times 10^{-9}$ that was chosen by and is known only to the NIST Mass & Force Group.

- Two year time frame: October 1st 2011 – October 1st 2013
Two key ideas behind this measurement

Å Independence
   • A new team to get a fresh start and a different look at things.

Å Blindness
   • Not knowing the result frees us from experimenters bias.
The NIST-3 apparatus

Technical Facts:

- \( IB = 490 \) Tm
- \( I = 10 \) mA
- 8 cm travel
- PtIr mass (K85) / stainless masses
- Wheel balance
- Knife edge bearing
- Multifilament bands
- 5 A Superconducting solenoid provides field.
- Open field (no flux return)
- Fiberglass vacuum chamber
Mass side stirrup

L = 4.18 m,  
m = 25 kg

Wobble frequency: 0.537 Hz  
Pendulum frequency: 0.241 Hz  
Bounce frequency: 16 Hz  
Sensitivity to torques: $2 \times 10^{-5}$ Nm  
Sensitivity to horiz. forces: $6 \times 10^{-5}$ N
Magnetsystem

US, Upper Solenoid
10 modules
10,710 turns ea.

UT, 3136 turns
LT, 3136 turns

LS, Lower Solenoid
10 modules
10,710 turns ea.

MC, 3 concentric Coils 826 turns Ea.

Moving coil
43.2 x 43.2

Force between US and LS:
@5A: 4821 N
@2A: 771 N

Currents:
1. Main 5.25 A (mostly)
   US: cw
   UT: cw
   LT: ccw
   LS: ccw

2. Skew 12.6 mA
   US: cw

3. Trim 59.2 mA
   UT: ccw
   LT: ccw

0.254 mm dia NbTi - Cu wire
On G10 bobbins, ~320 km wire
Concerns regarding the magnet system

- Surface currents due to Meissner Effect
  - BL during force mode is different due to persistent surface currents.

- Transient effects
  - Current ramp in moving coil changes super current.

- Transformer effect
  - AC in moving coil induces AC in super conductor. AC-AC coupling has net DC force.

- Iron
  - Nearby ferromagnetic material changes BL during force mode.

Iron cylinder, 24.3 kg

No change in $h$ observed!
Careful measurement performed in Nov. ‘12 indicates good agreement between 2A & 5A data. The difference is $25 \pm 18$ ppb is hardly significant. We put the systematic uncertainty Of this at 18 ppb.

Previously, as reported at CPEM 2010, we found an effect that was as large as 100 ppb. At that time the experiment was not controlled as well. We believe that the hysteresis imprinted in the knife edge was not sufficiently erased. Also: The knife edge was replaced after this data was taken.
Stability of the magnetic field

Diagram showing the variation of BL @ Min (Tm) and Rel. Humidity (%) over UTC time since 1/1/2012 in days. The data is represented with various markers and lines.
Knife edge

- Knife edge and flat are made from WC.
- It is coated with diamond like carbon.
- WC is magnetic.
- Knife edge was changed on 06/25/2012.
- Old knife edge was in use from 2010 to 2012.
Calibrations -- Mass

Drift rate: 9 µg/a
Calibrations -- Resistance

Slope: 0.385 ppb/day

09/06/2012 (249) Put this resistor in WB
Measurement procedure

Â Servo moving coil to top, balance is controlled with counter mass motor
Â Measure a velocity, coil sweeps from top down, takes about 40s
Â Measure a velocity, coil sweeps from bottom up, takes about 40s

Repeat 4x

Â Servo balance to middle, perform ZFLEX0 (+35 mm, -16 mm,..).
Â Switch balance control to the moving coil. Move masses close
Â Depending on how well the system is balanced the knife edge moves a little.
Â Perform ZFLEX1 to erase the imprint of this motion on the knife edge
Â Put Counter mass on, perform ZFLEX2 &3 takes about 5 min
Â Weighing takes about 100 s
Â Put Main mass on, perform ZFLEX3 takes about 5 min
Â Weighing takes about 100 s
Â Take Main mass off, perform ZFLEX3 takes about 5 min
Â Weighing takes about 100 s

Repeat Nx (typical 11-13)

Â Servo balance to middle, remove masses, switch control to CM motor
Â Servo balance to top, balanced is controlled with counter mass motor
Â Measure a velocity, coil sweeps from top down, takes about 40s
Â Measure a velocity, coil sweeps from bottom up takes about 40s

Repeat 3x
One Velocity Sweep

247 data points

Std. Dev $8.7 \times 10^{-4}$ Tm
All Data since December 2012

Notes: black points: as measured
colored points: corrected
Only type A uncertainties (k=1) shown

$h_{adj}/h_{90\text{-}1}$ (ppb)

- Pfr, 1 kg, 5A
- Pfr, 1 kg, 5A
- SS, 1 kg, 5A
- SS, 0.5 kg, 5A
- SS, 0.5 kg, 2A
- SS, 1 kg, 5A
- Pfr, 1 kg, 5A
- Pfr, 1 kg, 5A
Results, Pt-Ir only

Only statistical uncertainties shown

<table>
<thead>
<tr>
<th>Sample</th>
<th>h_{adj}/h_{90-1} (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(470 ± 73)</td>
</tr>
<tr>
<td>K85</td>
<td>(1 879 10 73 10) kg</td>
</tr>
<tr>
<td>K85</td>
<td>(1 771 10 113 10) kg</td>
</tr>
</tbody>
</table>
## Preliminary Uncertainty Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance mechanics</td>
<td>50†</td>
</tr>
<tr>
<td>Electrical (weighing)</td>
<td>20</td>
</tr>
<tr>
<td>Electrical (moving)</td>
<td>20</td>
</tr>
<tr>
<td>Alignment</td>
<td>20</td>
</tr>
<tr>
<td>Velocity</td>
<td>20</td>
</tr>
<tr>
<td>Data analysis</td>
<td>20†</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>18</td>
</tr>
<tr>
<td>Mass measurement</td>
<td>15</td>
</tr>
<tr>
<td>Statistical</td>
<td>15†</td>
</tr>
<tr>
<td>g</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>73</strong></td>
</tr>
</tbody>
</table>

†) not completely understood, more investigations needed.
Let's open the envelope.

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x4218
In the last 21 months measurements with the NIST-3 watt balance have been performed.

The measurements were done independent of previous measurements.

The experiment was “blind”. The precise values of the masses used were revealed on 18\textsuperscript{th} June 2013 yielding a new result:

\[
\begin{array}{c}
\text{1} \\
(143 \quad 73) \\
10
\end{array}
\]

This evaluation is preliminary. Work on the error budget is not yet complete.

We will complete our investigations in the fall and aim for a publication early next year.
Why does the new NIST number differ from the old?

Å We don’t know yet...
Å We are still investigating this difference.
Å Many things were changed, some irreversibly:
   ï Grounding, Shielding, electrical power, PJVS,..
What happened since June?

1. Warmed up and cooled down the superconducting solenoid.
2. We installed new fiber coupled, battery powered current sources for main coil and counter mass motor.
3. Installed a new flexure for the mass pan.
4. Improved mass exchange parameters.
5. Upgrade the moving coil interferometers to have fiber coupled pick-ups.
6. Test realization with an unknown mass
The flexure and the parameters allow for better mass transfers.
The flexure and the parameters allow for better mass transfers.

Points like this were not used in the final determination.
Test realization of mass at 1kg SS

We bought a new stainless mass
Å E2
Å Not calibrated
Å Minimal surface

Mass goes on NIST-3 watt balance. We use
\[ h = h_{90}(1+143\text{ppb}) \]
to determine \( m_{WB} \)

NIST mass group determines \( m \)
How do they compare

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>1-σ uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watt balance(^{(1)})</td>
<td>1 kg + 342 µg</td>
<td>73 µg</td>
</tr>
<tr>
<td>Mass group</td>
<td>1 kg + 324 µg</td>
<td>13.5 µg</td>
</tr>
</tbody>
</table>

\(^{(1)}\)Note: The watt balance measurement contains a 11.3 µg correction due to the magnetic forces on the mass in the field of the superconductor.
Summary

Å We measured using the NIST-3 watt balance:

\[
\frac{\text{?}}{\text{?}} - 1 = (143 \pm 73) \times 10
\]

Å A blind mass measurement was performed at the 1 kg level. The difference to the value given by the NIST mass group was

\[- \text{?} = 18 \text{ g} \pm 74 \text{ g}\]

Å We are currently working on one more measurement campaign using K85 and we hope for

\[- \text{?} < 50 \times 10\]
Thank you for your attention!

This vs. that

New NIST-4 magnet

1750 l of LHe to run NIST-3 for 7 weeks.