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Electrical Methods to Monitor the Stability of the Kilogram

\[
\gamma = \frac{\{N\}_{90}}{\{N\}_\text{SI}} = \frac{\{w\}_{90}}{\{w\}_\text{SI}} = \frac{\{J\}_{90}}{\{J\}_\text{SI}} = \frac{\{...\}_{90}}{\{...\}_\text{SI}} = \frac{\{h\}_{90}}{\{h\}_\text{SI}} \quad \text{fixed}
\]

- Ampere Balance
- Voltage Balance
- Watt Balance
- Joule Balance
- CIPM Parts in $10^8$

\[
h_{90} = \frac{4}{K_{J-90}^2 R_{K-90}}
\]
The joule balance, in physical significance, is based on a mechanical and electromagnetic joule equivalence.

\[
m g (z_1 - z_2) = [M(z_1) - M(z_2)] I_1 I_2
\]

On the left hand of the equation is the geopotential energy change when the test mass is moved along the vertical from \( z_1 \) and \( z_2 \) while in the right hand, it is the electromagnetic energy change.

\[
h = \frac{4 mg (z_1 - z_2)}{K_{j-90} R_{K-90} ([M(z_1) - M(z_2)] I_1 I_2)_{90}}
\]
the Apparatus of Joule Balance
## Present Experimental Uncertainty

<table>
<thead>
<tr>
<th>Uncertainty components</th>
<th>Contribution (k=1, ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutual Inductance</td>
<td>0.1</td>
</tr>
<tr>
<td>Current Source</td>
<td>0.2</td>
</tr>
<tr>
<td>Coil System (exothermic effect)</td>
<td>22</td>
</tr>
<tr>
<td>Balance System</td>
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<tr>
<td>test weight</td>
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<tr>
<td>Length Measurement</td>
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<tr>
<td>gravity</td>
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<tr>
<td>aerostatic buoyancy</td>
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</tr>
<tr>
<td><strong>Combined Uncertainty</strong></td>
<td><strong>25</strong></td>
</tr>
</tbody>
</table>
Measurement Techniques Proposed:

- DC integral with V/F converter method
  - $U$: 4ppm($k=1$)

- AC low frequency Compensation Method
  - Linear extrapolation is needed to obtain a DC value of mutual inductance
  - $U$: 0.5ppm ($k=1$)
  - Better but time-consuming, difficult to be ATE (auto test equipment)

- DC Standard Square-wave Compensation Method
  - $U$: 0.22ppm($k=1$)
  - Fast, ATE, DC value of mutual inductance
Principle of Standard Square-wave Compensation method

\[ S = \int_{I_1}^{I_2} u dt = M (I_2 - I_1) \]

\[ M = \frac{S}{I_2 - I_1} = S_E + (S - S_E) \frac{E_1 \Delta T}{I_2 - I_1} \]

\[ S_E = E_1 (I_2 - T_1) = E_1 \Delta T \]

\[ M_1 = R \Delta T \frac{E_1}{I_2 R - I_1 R} \left( 1 + \frac{\Delta S}{S_{E1}} \right) \]

\[ 10^{-3} \]

\[ 10^{-6} \sim 10^{-7} \]
A superconducting coil for Exciting coils

- A superconducting coil was designed and fabricated.
- To maintain the superconducting coil in operation for a long time and economize the expensive liquid helium, it is an attempt to utilize cryocooler to refrigerate superconducting coil.
- The self-inductance of superconducting coil is 20H!
- The Standard Square-wave compensation method is used to measure $M$. 
Advantage of using superconducting coil

- equivalent circuit of an impure mutual inductor

\[
M = M_0 - C_{12} R_1 R_2 + a \omega^2
\]

Inter capacitance correction of the mutual inductance is avoided
Preliminary Measurement results of superconducting coil

Mutual inductance of superconducting coil (\( /0.3s \))

Relative std. 6E-7
The superconducting coil was transported to the workshop for some improvement of the mechanical stability of the coil frame.

The Meissner effect will be investigated before the application of superconducting coil in Joule balance.

- In weighing mode, the superconducting coil is in the field produced by itself and movable coil with current.
- In mutual mode, the superconducting coil is only in the field produced by itself.

Some additional uncertainties will be existed due to the difference of two modes. A kind of novel coil system instead of superconducting coil is being devised.
Device improvement: coils’ system

8 exciting coils
Difficult to alignment
Heavy heating questions

2 exciting coils
Easy to alignment
Exothermic effect adjusted by current source
Device improvement: Balance System

- A mass comparator with 1ug resolution will be ordered to replace the balance system of long beam in use at present.
- A compact system will be built and be placed in a vacuum chamber, length measurement can be improved at the same time.
- The stability of balance system can be improved.
Device improvement: Length Measurement with positioning methods

Laser interferometer for the displacement measurement in vertical direction

The balance system with Liquid Damping device and Piezoelectric Ceramic in the suspension system.
## Our Target Uncertainty

<table>
<thead>
<tr>
<th>Uncertainty components</th>
<th>Contribution (k=1, ppm)</th>
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<td>Coil System (exothermic effect)</td>
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<tr>
<td>test weight</td>
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<tr>
<td>Length Measurement</td>
<td>0.1</td>
</tr>
<tr>
<td>gravity</td>
<td>0.01</td>
</tr>
<tr>
<td>aerostatic buoyancy</td>
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<tr>
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## Our Timetable for Achieving Our Goals

<table>
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<tr>
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<th>2011</th>
<th>2012-2013</th>
<th>2014</th>
<th>2019</th>
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<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^{-7}(10^{-8})$</td>
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<td>PJVS</td>
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<tr>
<td><strong>Alignment</strong></td>
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<td>$10^{-6}$</td>
<td></td>
<td>$10^{-7}(10^{-8})$</td>
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<tr>
<td><strong>Length Measurement</strong></td>
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<td>Laser lock $10^{-6}$</td>
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<td>$10^{-7}(10^{-8})$</td>
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<tr>
<td><strong>Current Source</strong></td>
<td>$10^{-7}$</td>
<td>$10^{-8}$</td>
<td></td>
<td>$10^{-8}$</td>
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</table>
THANK YOU!