

Developing a Joule Balance Mode for the METAS Watt Balance

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Since the coming into effect of the new SI system in 2019, the kilogram is linked to the Planck constant h . However, the existing realization experiments maintained by various national metrology institutes do not yet yield results that show satisfactory agreement. In this regard, METAS aims to develop a joule balance mode for its existing watt balance, leading to a dual-mode joule-watt balance. The traditional watt balance establishes a comparison between virtual mechanical and virtual electrical power at a fixed vertical position, while the joule balance compares mechanical and electrical work performed over a continuous range. With the implementation of a joule-watt balance, METAS aims to increase the reliability of its existing kilogram realization experiment.

This development introduces several technical challenges, including the precise alignment of the magnetic system and coil, synchronization of trigger events, and mitigation of thermal effects on the magnetic field. Addressing these issues and successfully implementing a joule balance method will contribute towards independent and precise mass determinations at national metrology institutes.

1. Introduction

Since 2019, the definition of the mass unit is no longer given by an artifact, but is now linked to the Planck constant h . Currently, there are three different approaches in use to realize the new definition of the mass unit: The x-ray crystal density method, the watt balance and the joule balance method. However, the existing realizations do not yet agree to a satisfactory degree (figure 1). By international agreement, national metrology institutes hence refrain from independently realizing the kilogram unit, until better agreement among kilogram realization experiments is achieved [4, 8].

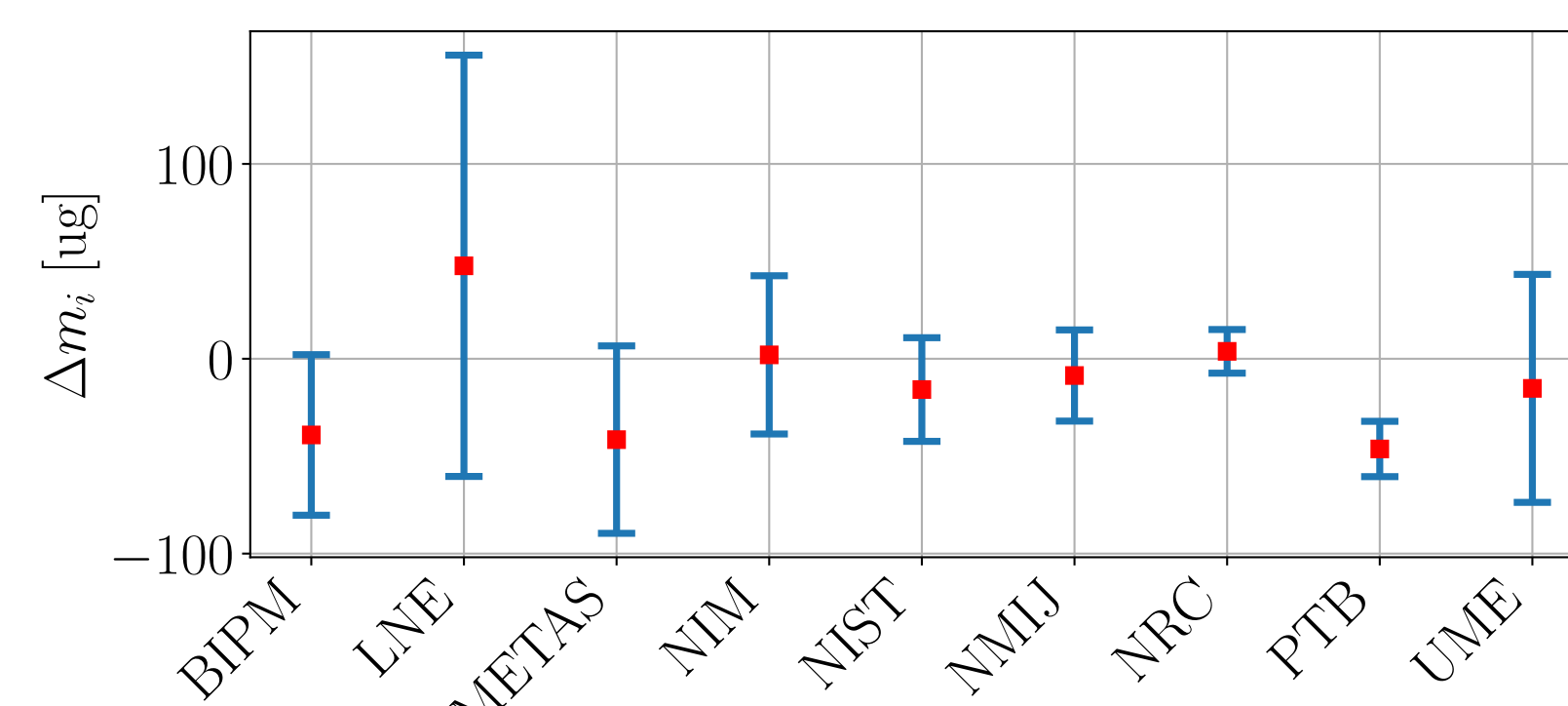


Figure 1: Results from the key comparison 2021 as reported by [4]. The figure shows the differences Δm_i between mass values attributed to 1 kg mass standards and the key comparison reference value (KCRV) for each national metrology institute i . Figure is reproduced from fig. 3 in [4].

2. Working principle of the watt balance

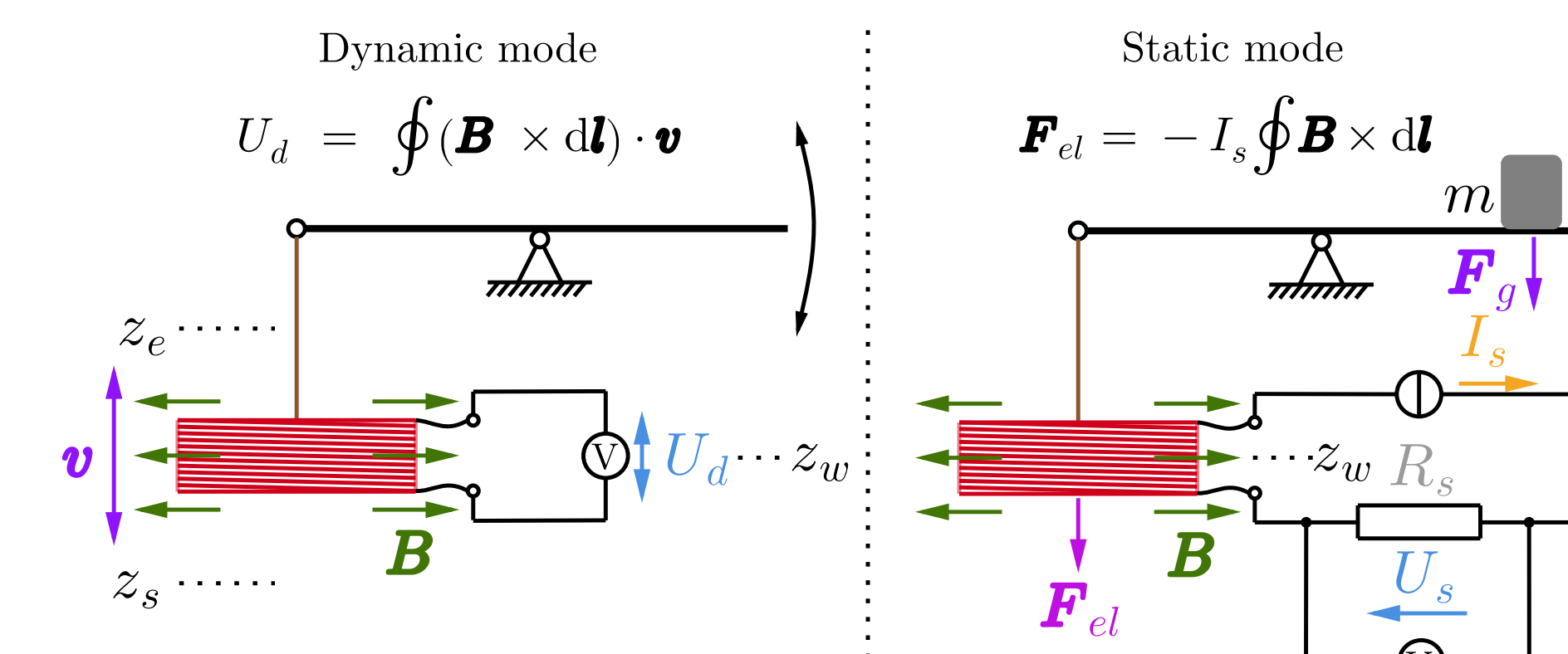


Figure 2: Working principle of the watt balance modes. Virtual mechanical power is compared to virtual electrical power at the fixed vertical position z_w . The red lines visualize the windings of the coil. The figure assumes, that the distances of the points of action for F_{el} and F_g from the pivot point of the balance are identical.

The principle of the watt balance relies on a comparison between virtual mechanical and virtual electrical power (figure 2). In the dynamic mode (inducing), a coil is moved with velocity $v = dz/dt$ in a radial magnetic field, which induces a voltage U_d in the coil. In the static mode (weighing), a current I_s is supplied to the coil such that $F_{el} = F_g$. Using electrodynamics (figure 2), one obtains

$$\frac{mg}{I_s} = U_d \frac{dt}{dz} \Leftrightarrow mgv = U_d I_s. \quad (1)$$

Here, g is the gravitational acceleration at the location of m . The voltage U_d and the current I_s are related to the Planck constant h by means of the quantum Hall and Josephson effects [6, 7].

References

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3. Why develop a joule balance mode?

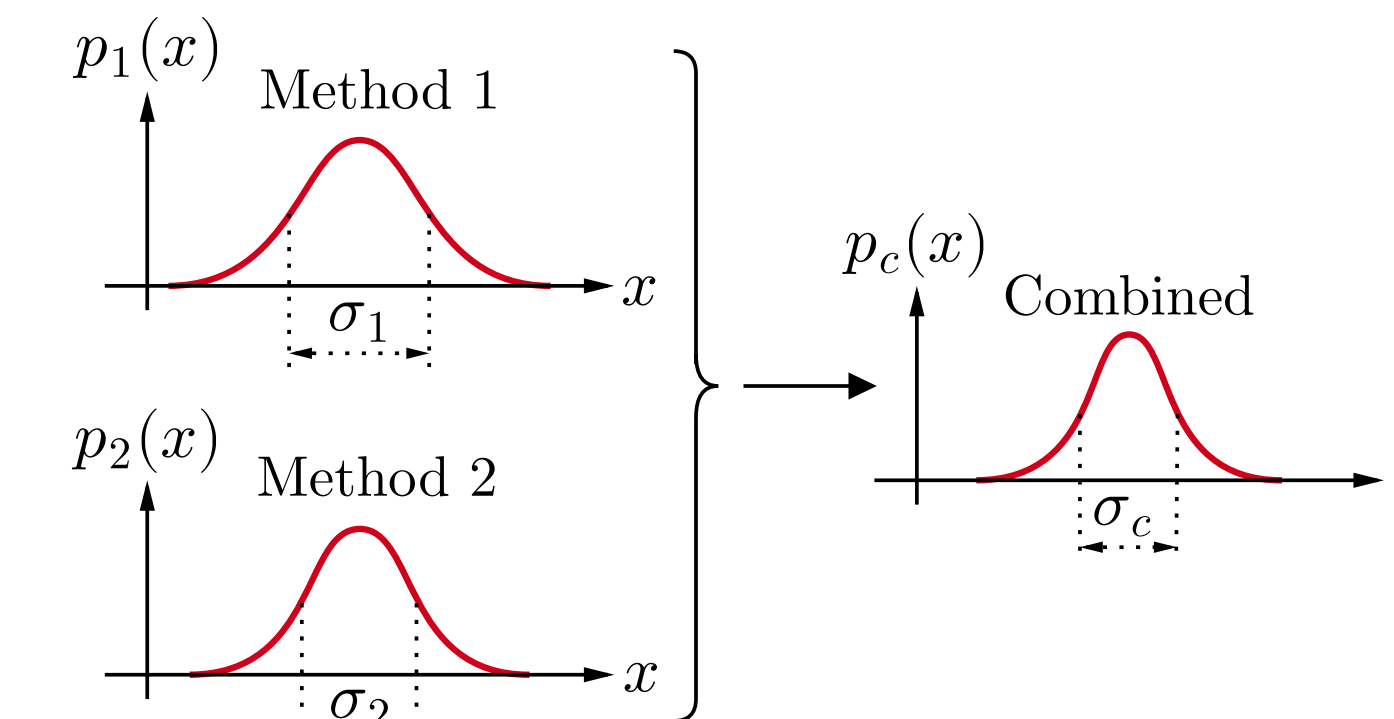


Figure 3: Given two methods to determine some quantity x with densities $p_1(x)$ and $p_2(x)$, it is possible to compute a weighted average $p_c(x)$, which – given the correlation coefficient between the methods is sufficiently low – has a lower uncertainty $\sigma_c \leq \sigma_1, \sigma_2$.

Motivated by the discrepancies among the various kilogram realization experiments (figure 1), METAS has decided to develop a joule balance mode for its existing watt balance. The key idea is to use two distinct methods to determine the mass of the same weight. Combining both methods by means of a weighted average can be shown to lead to a reduction in measurement uncertainty, if the correlation coefficient between the methods is sufficiently low (figure 3). Furthermore, comparing results obtained by two different approaches implemented in the same apparatus will foster confidence in the existing setup. Once the joule balance mode is available, the mass of the same weight can be determined by both the watt and joule balance methods.

4. Developing a joule balance mode

Instead of performing a comparison between virtual mechanical and electrical powers at a fixed coordinate z_w , the joule balance approach establishes a comparison of mechanical and electrical work performed over the full range $[z_s, z_e]$ (figure 4). Mathematically, this is expressed by means of the integral

$$m \int_{z_s}^{z_e} \frac{g}{I_s} dz = \int_{z_s}^{z_e} U_d \frac{dt}{dz} dz = \int_{t(z_s)}^{t(z_e)} U_d dt \quad (2)$$

of eq. (1) with respect to z . The feasibility and successful implementation of a joule balance have been demonstrated [5]; and watt balances are well-established [1, 2, 3]. However, no experiment has yet combined both approaches in a single apparatus. Realizing this novel approach is what METAS aims to achieve in the future.

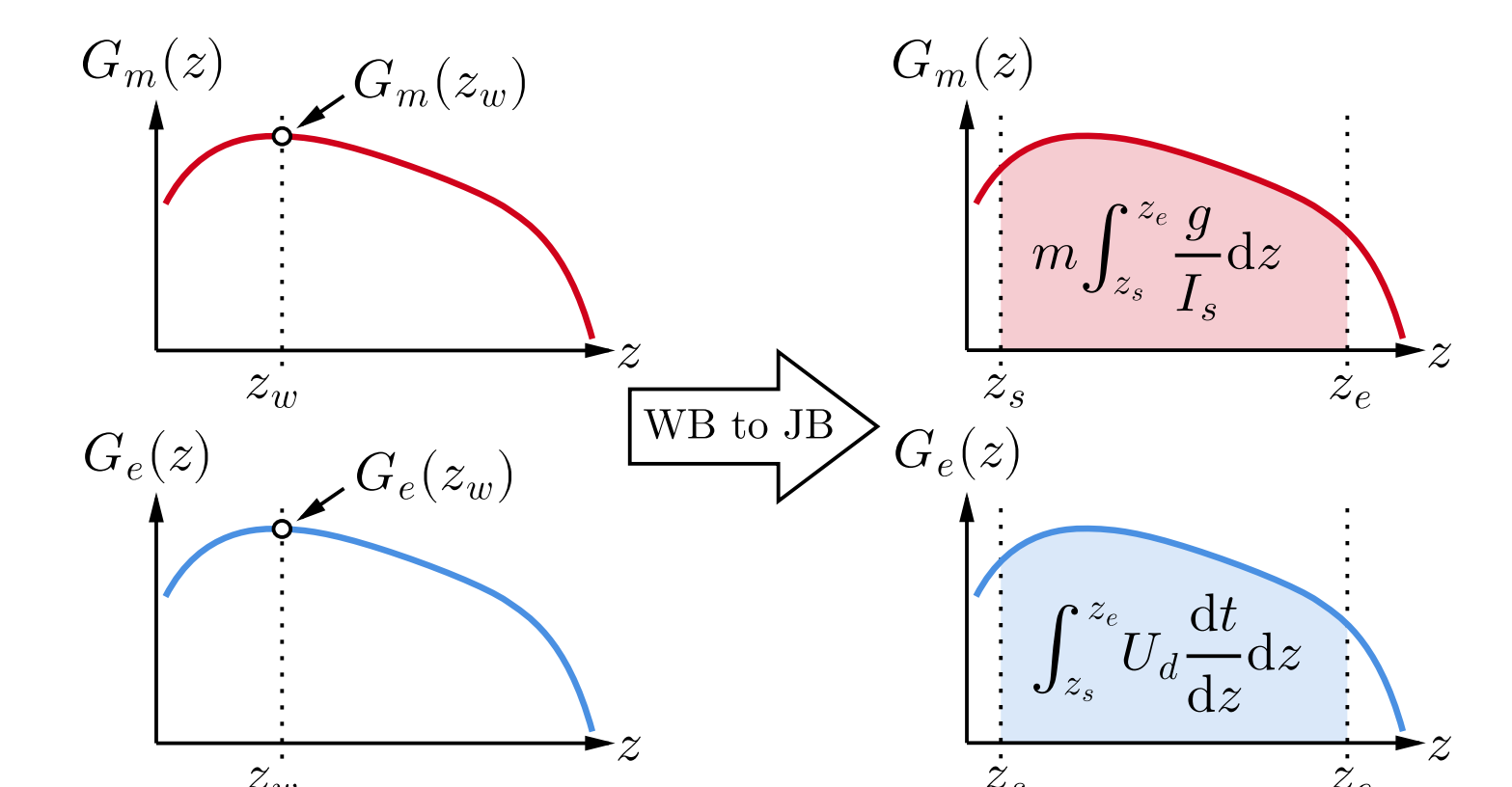


Figure 4: Note, that $G_m(z) = mg(z)/I_s(z)$ and $G_e(z) = U_d(z)(dz/dt)^{-1}$. The left hand side shows the watt balance mode, whereas the right hand side visualizes the joule balance mode.

5. Challenges and outlook

Developing a joule balance mode for the existing watt balance at METAS will require tackling several challenges. A key difficulty will be the alignment of the electrical and mechanical forces when performing multiple weighings (static modes) at different positions along the vertical axis z . Furthermore, synchronization of trigger events will be another challenge. With respect to eq. (2) for example, exact knowledge of the timestamps $t(z_s)$, $t(z_e)$ and the associated positions z_s , z_e will be required. The temperature dependency of the magnetic field B presents yet another challenge, as the left-hand side of eq. (2) necessitates multiple weighings at incremental positions in z . The currents I_s used for the weighings lead to heating of the coil and nearby parts, resulting in small changes of magnetic field strength. In addition to this, the evaluation of eq. (2) also presupposes knowledge of the gravitational acceleration profile $g(z)$ for the range $[z_s, z_e]$.

In the near future, METAS will be working on solving these challenges and developing a double-mode joule-watt balance; that is, an experimental device that is able to realize the mass unit definition by means of both the joule and watt balance approaches. This work will contribute towards independent and precise kilogram realizations by national metrology institutes and will foster confidence in the existing kilogram realization experiment at METAS.