

# Towards a Quantum Mass Standard with the Tsinghua Tabletop Kibble Balance

Shisong Li<sup>†</sup>, Weibo Liu, Nanjia Li, Yongchao Ma, Kang Ma, Wei Zhao, Songling Huang, Xinjie Yu

Department of Electrical Engineering, Tsinghua University, Beijing 100084, China

## GOAL & GENERAL DESIGNS

- The goal is to develop the next-generation Kibble balance for NMI-level mass realizations following the new SI.
- Pioneer the development of a compact, highly accurate, robust, cost-effective, and user-friendly Kibble balance.
- 10 g to 1 kg mass calibration with a measurement uncertainty of below 50  $\mu\text{g}$ .
- Size: 1 m in height and 0.35 m in diameter.
- An advanced one-mode, two-phase (OMTP) measurement scheme is employed.
- The magnet-moving mechanism is used during the velocity measurement.

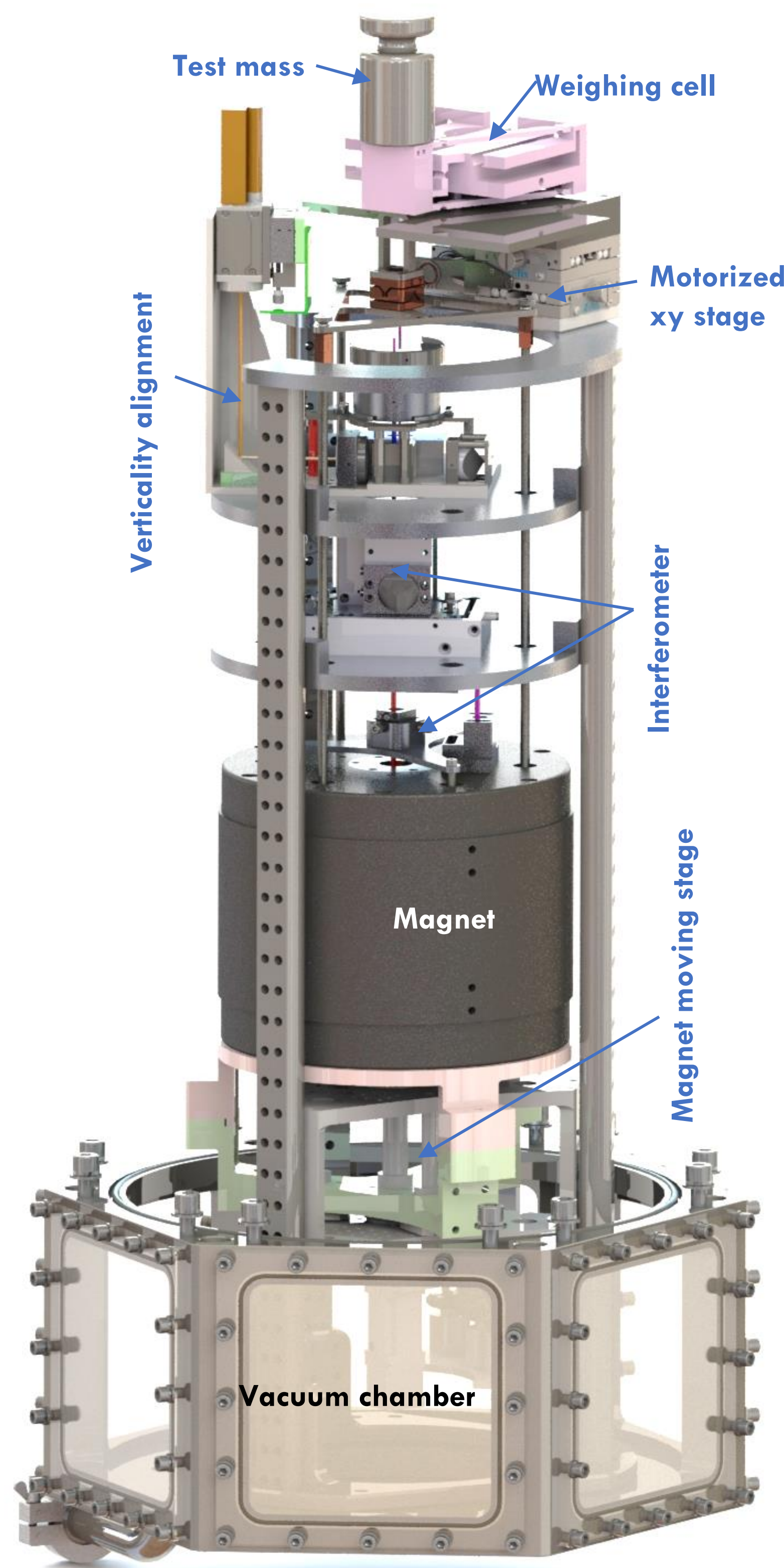


Fig.1 Design of the Tsinghua Tabletop Kibble Balance.

## A NOVEL TABLETOP MAGNET SYSTEM

- A highly efficient Kibble balance magnet system:  $H = 180 \text{ mm}$ ,  $\Phi = 220 \text{ mm}$ ,  $m \approx 40 \text{ kg}$ . Air Gap:  $h_a = 50 \text{ mm}$ ,  $r_a = 80 \text{ mm}$ ,  $B \approx 0.6 \text{ T}$  (NdFeB).
- New feature I: Inner yoke compensation: The uniform field range ( $\Delta B/B < 1 \times 10^{-3}$ ) is enhanced to 35 mm, increasing by over 50%.
- New feature II: Easy splitting operation. Open/close forces are reduced to tens of kilograms compared to the conventional kN-level.

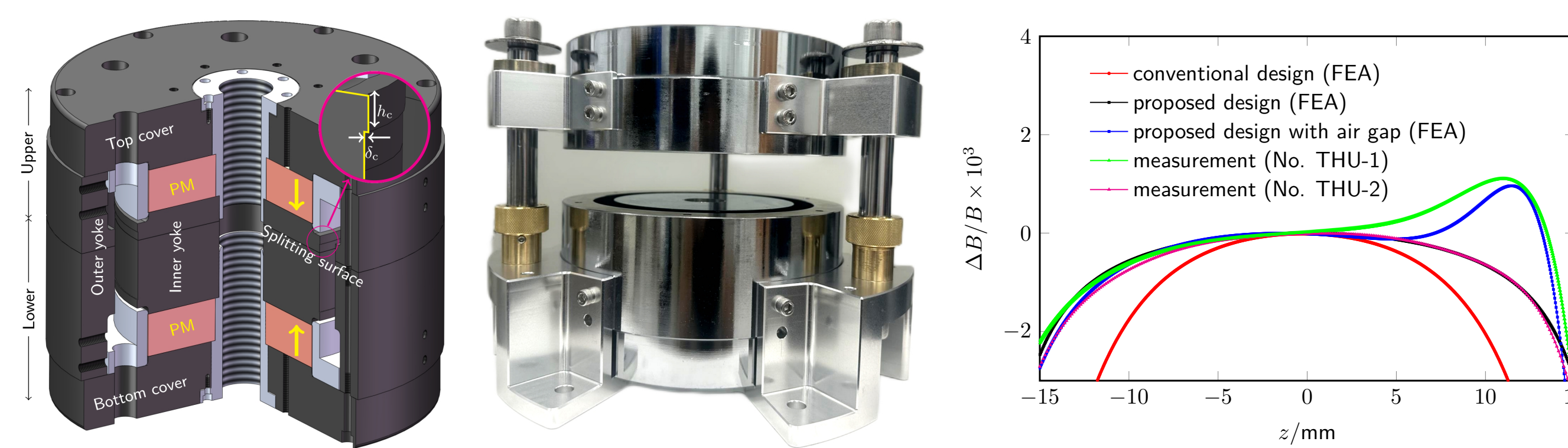


Fig.2 Tsinghua tabletop Kibble balance magnet system.

Left: CAD model. Middle: Levitation in opened status. Right: Magnetic profile.

## A TWO-STAGE BI-POLAR CURRENT SOURCE

- A bi-polar current source with an output capacity of  $\pm 20 \text{ mA}$  and stability of a few nA/A @ 30 mins.
- Stage  $I_1$  (Keithley 2410): range 20 mA, resolution 0.5  $\mu\text{A}$  + Stage  $I_2$  (Keithley 6221): range 2  $\mu\text{A}$ , resolution 0.1 nA.
- In the weighing phase, a constant force (CF) scheme is realized by servo-controlling the coil position.
- In the velocity phase, a constant current (CC) scheme is employed to minimize the current effect.

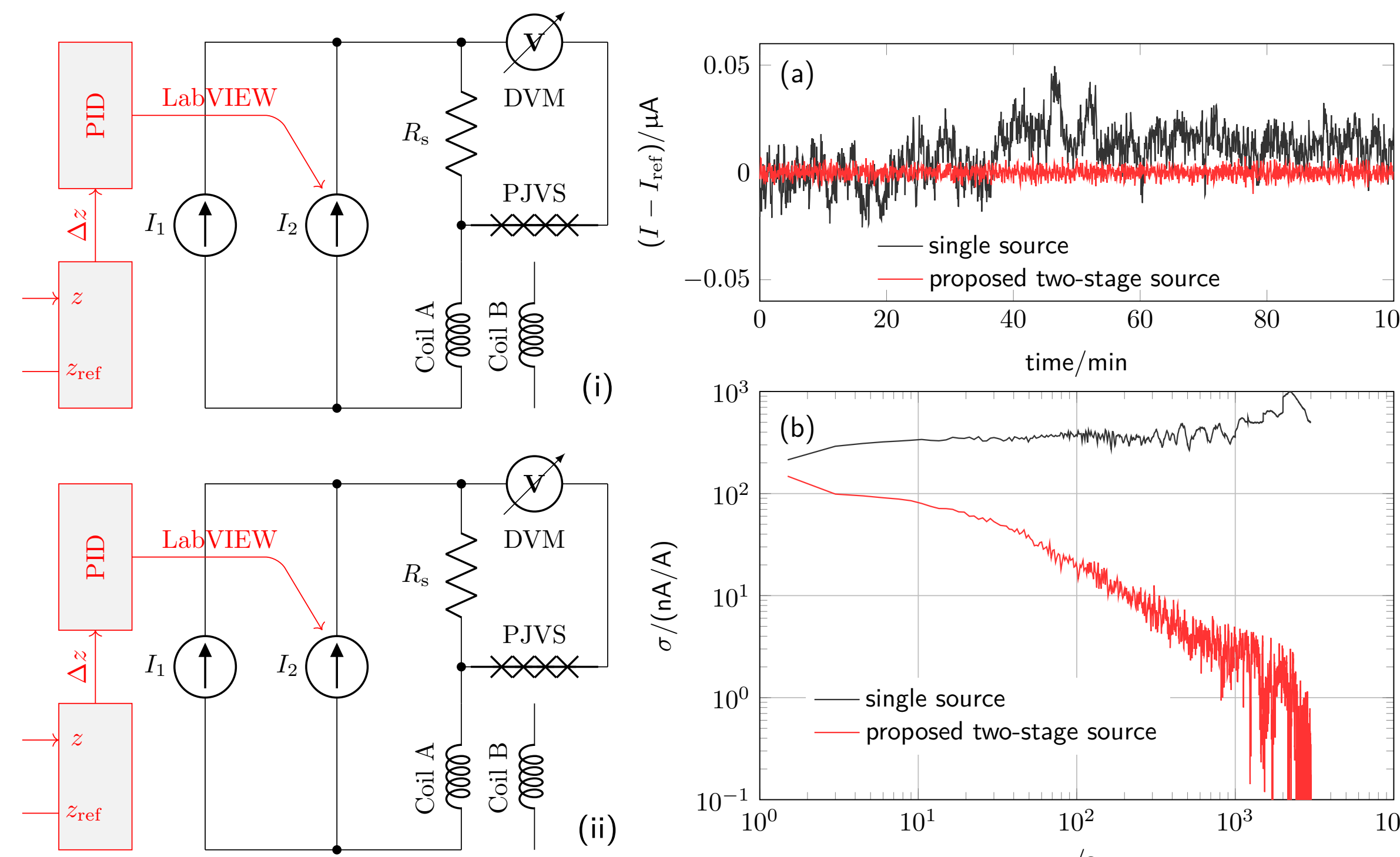


Fig.3 Left: Operating of the current source in the two measurement phases. (i) CF operation scheme and (ii) CC operation scheme. Right: Experimental result at the CC scheme.

## A CUSTOMIZED WEIGHING UNIT

- Weighing resolution at the microgram level and a dead load capacity of several kilograms.
- A capacitor sensor is used for displacement detection, showing a higher measurement resolution than optical sensors.
- An active servo control capacity of several tens of grams with adjustable PID parameters.
- $1\sigma < 10 \mu\text{g}$  is obtained for a 10-hour test in air.

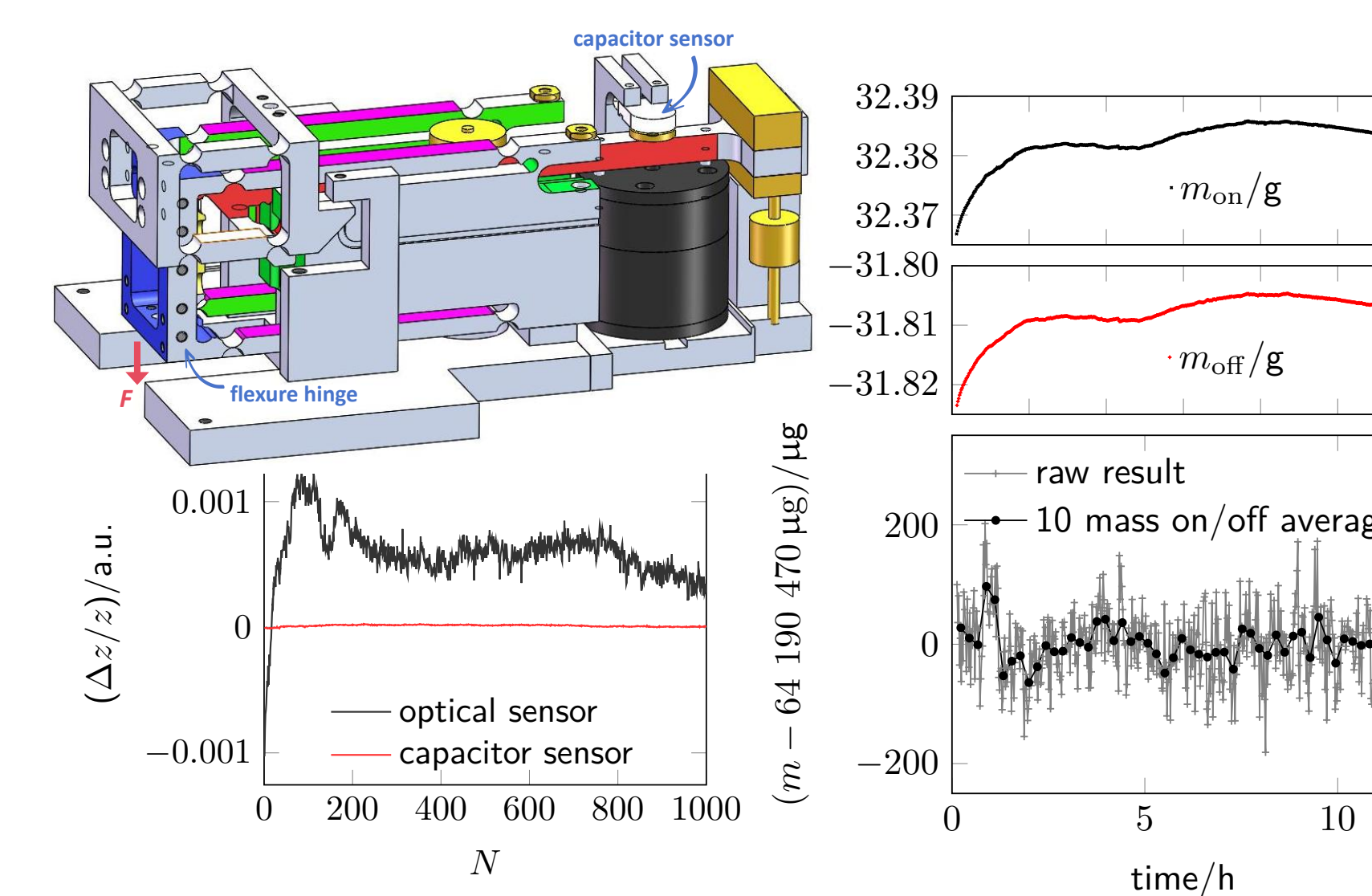


Fig.4 Left: Weighing unit design and displacement measurement resolution. Right: A mass measurement test (64 g mass load in air).

## AN ADVANCED OMTP MEASUREMENT SCHEME

- A bifilar-coil power regulator is proposed to eliminate thermal-magnetic errors.
- Keep coil ohmic power constant over time, and  $BI$  drift is mitigated through ABA or ABBA sequences.
- Thermal effect is reduced by 100 times compared to TMTP scheme and by about one order of magnitude compared to Traditional OMTP scheme.
- Breaking down size limitations for Kibble balances.

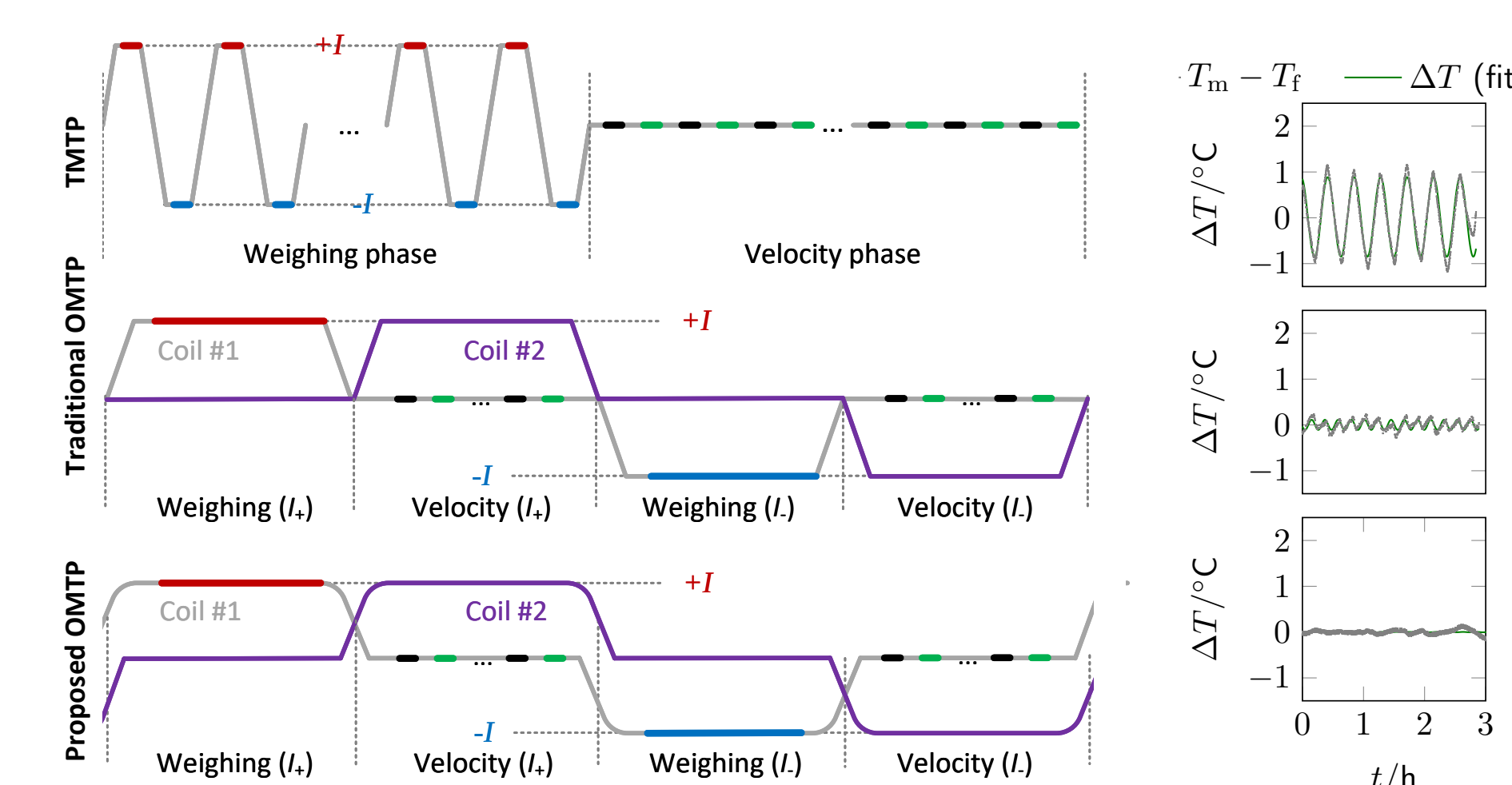


Fig.5 Proposed scheme and a test of the temperature change.

## MAGNET-MOVING MECHANISM

- Avoid displacing force-sensitive components, such as the weighing cell, and enable a broader magnetic profile measurement range.
- Error mechanism of far and near external fields is studied through FEA and experimental.
- An optimal weighing position and a monitor of the magnetic field surrounding the magnet system allows to suppress the external-field effect to the order of  $10^{-9}$ .

## OPEN HARDWARE INITIATIVE

- The design, manufacture, test tools and performance evaluation of shareware modules of the Tsinghua Kibble balance will be released.
- Experimenters are allowed to copy and build the same system with a limited number of licenses for non-commercial purposes.
- Leave the door of transferring to commercial partners, allowing experimenters to have the possibility to order components directly.

## CONCLUSION & OUTLOOK

- The Tsinghua tabletop Kibble balance aims to develop a compact, highly accurate, and cost-effective mass calibration instrument, focusing on enhancing measurement precision while maintaining compactness.
- Significant progress has been made in the design and implementation of key components, including a novel magnet system, a custom-designed weighing unit, a stable, dual-stage current source, etc.
- The subsequent phase is to integrate these components or subsystems into a cohesive whole.

## REFERENCES

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