【C1Po2A-01】Development of a cryogenic stepping motor using high-purity copper

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Abstract

We developed a stepping motor working in a cryogenic environment with small heat dissipation from it. The preliminary experiment was conducted at the temperature of 15 K using a GM cryocooler to estimate the heat dissipation on the motor. We measured the total heat dissipation of the motor with the high-purity copper coils and compared it to the motor with conventional ones. The measured heat dissipation was reduced by about 40 % when the motor rotation frequency was 0.0375 Hz (2.25 rpm).

Introduction

We employ a stepping motor as a part of three cryogenic holder mechanisms supporting the rotor of a cryogenically cooled superconducting magnetic bearing (SMB) as shown in **Figure 1**. The mechanism is to hold the rotor when the SMB is cooled down to the operational temperature of about 5 K, and it is actuated to release the rotor to achieve the levitation. A commercially available cryogenic stepping motor is one of the solutions, but it tends to generate the heat at the time of the activation.

An objective of the experiments is to estimate the motor heat dissipation and to investigate which of main four heat dissipations is dominant. We prepared two stepping motors with copper purity wire-based coils and conventional magnet wire-based coils, and compared their heat dissipations from each motor.

Design features

- Two-phase stepping motor by Tamagawa seiki inc.
- Two sets of stepping motors: motor with conventional coils and motor with high-purity coils. The purity of high-purity copper coils is 6N and the coils are annealed.
- Motor bearings are degreased and Molybdenum disulfide is coated on the bearing surfaces as solid lubricant. Silicon electromagnetic steel sheet are employed on a motor rotor and stator.
- The original aluminum chaises is replaced with G10.

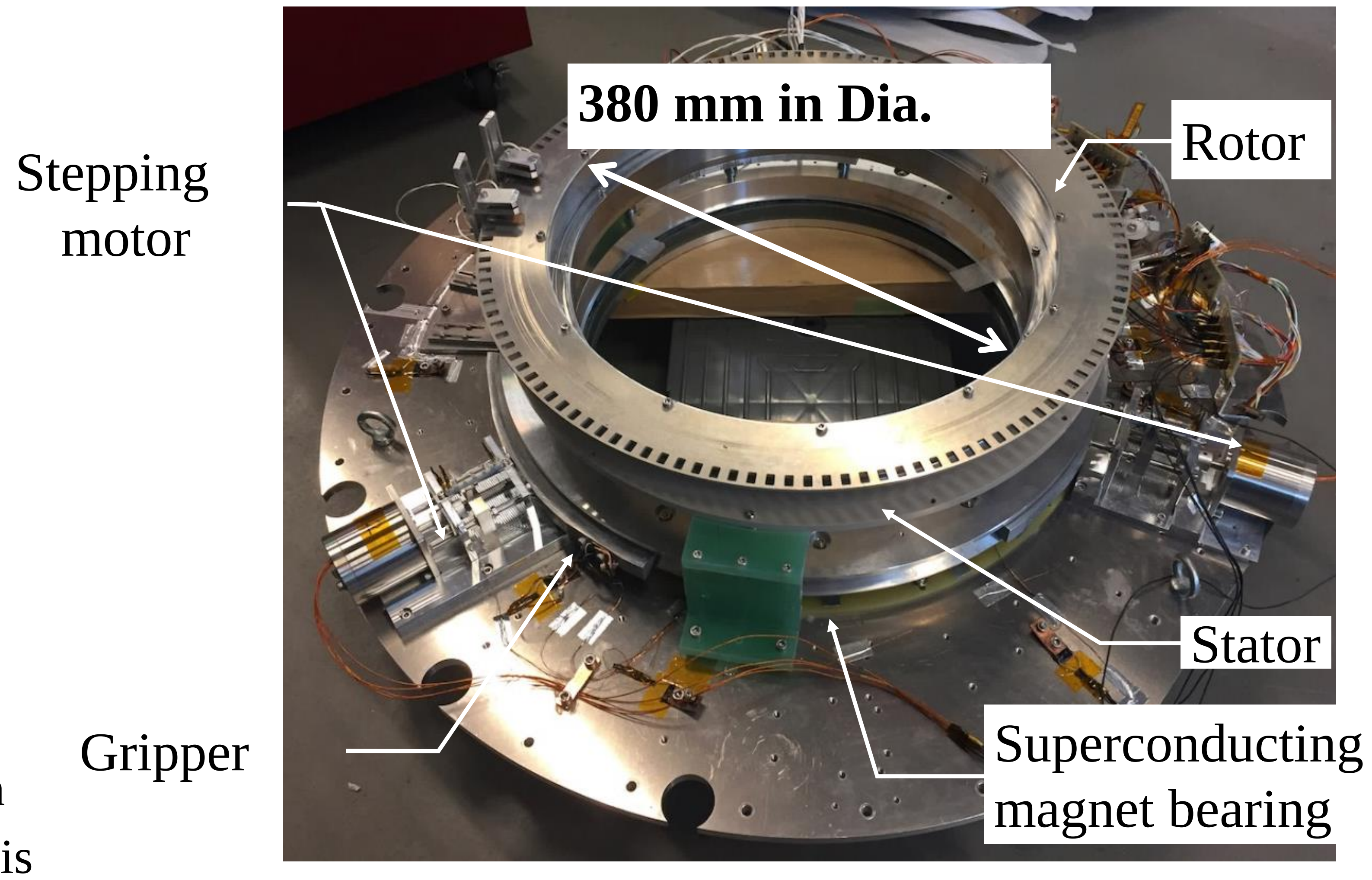


Figure 1. A breadboard PMU with three stepping motors (Only two of them appear here).

$$\frac{P_{total} - P_{copper}}{f} = a + b \cdot f$$

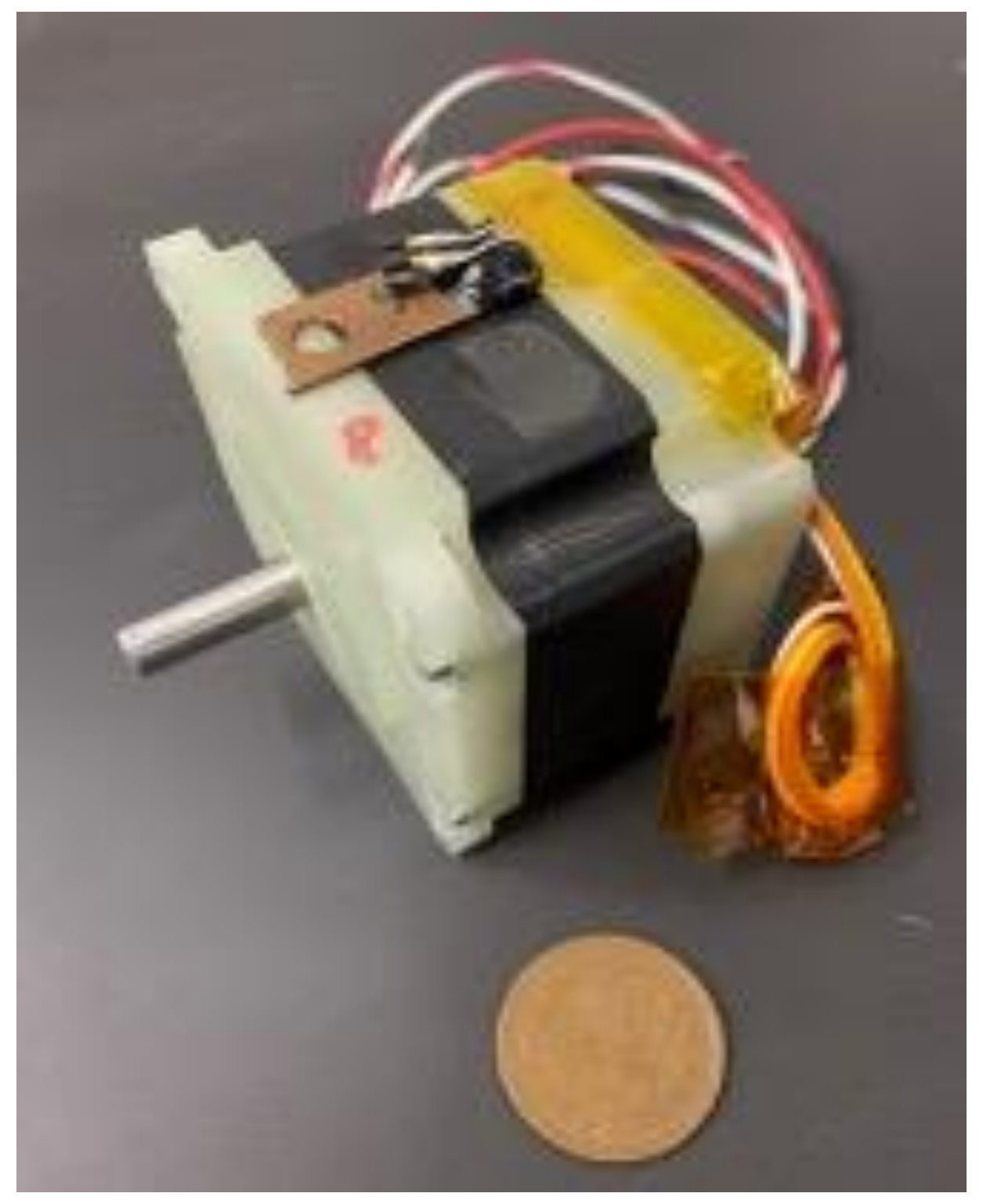
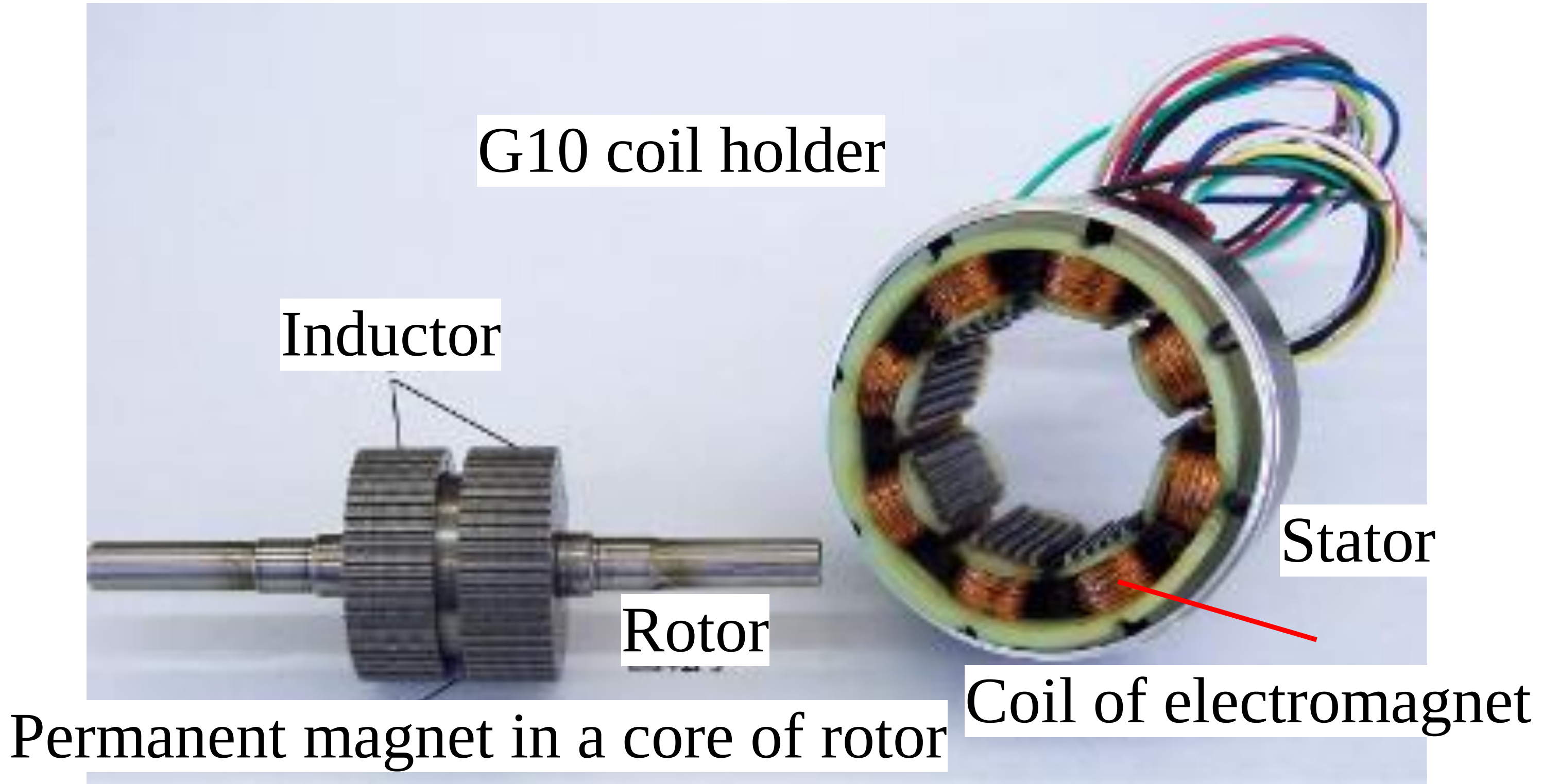
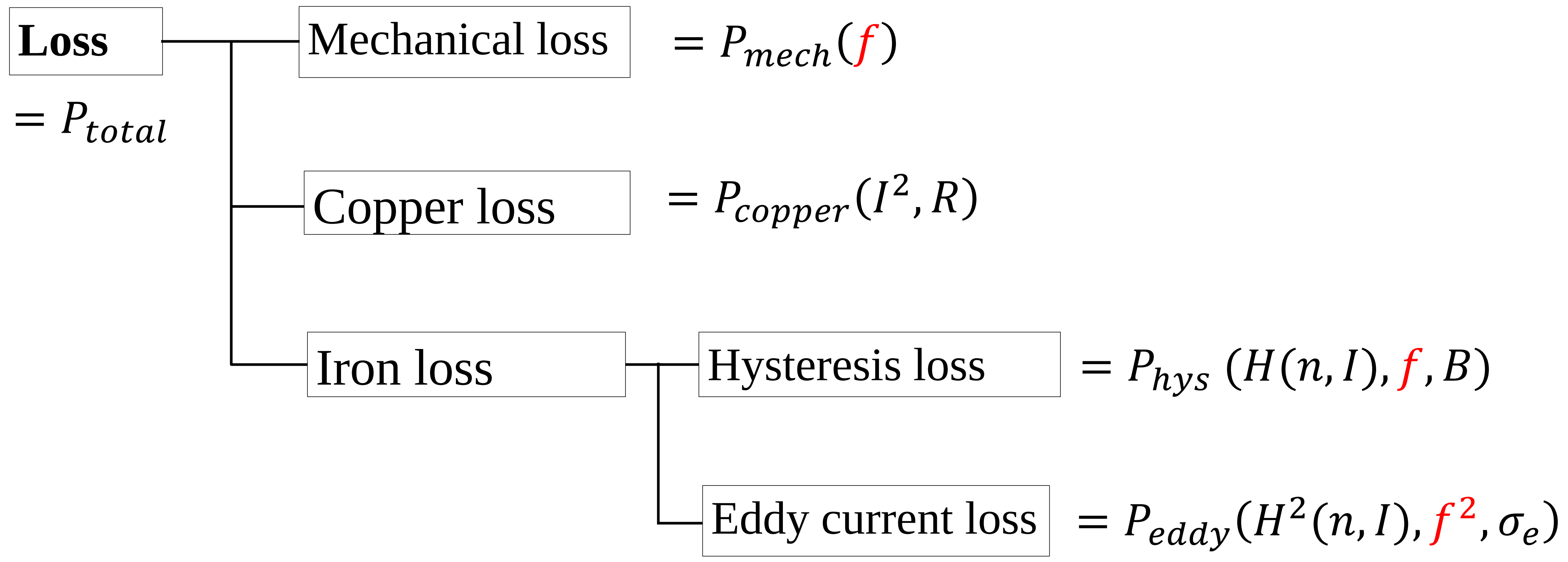


Figure 2. Stepping motor.



From *"https://technote.ipros.jp/entry/basic-motor4/"*

Figure 3. Inner structure of typical stepping motor.



Loss $= P_{total}$

Mechanical loss $= P_{mech}(f)$

Copper loss $= P_{copper}(I^2, R)$

Iron loss

Hysteresis loss $= P_{hys}\,(H(n, I), f, B)$

Eddy current loss $= P_{eddy}(H^2(n, I), f^2, \sigma_e)$

f: motor rotation frequency
I: alternating current applied to coil
R: coil electrical resistance
H: magnetic field of electromagnet
n: number of turns of coil
B: magnetic flux density of iron core
σ_e: electrical conductivity

Figure 5. Variety of losses on a motor.

$$P_{total} = P_{mech} + P_{copper} + P_{hys} + P_{eddy} \qquad (1)$$

The equation (1) can be rearranged into the equation (2) with frequency-dependent terms.

$$P_{total} - P_{copper} = a \cdot f + b \cdot f^2 \qquad (2)$$

Here, *a* is a mechanical + hysteresis loss constant and *b* is an eddy current loss constant.

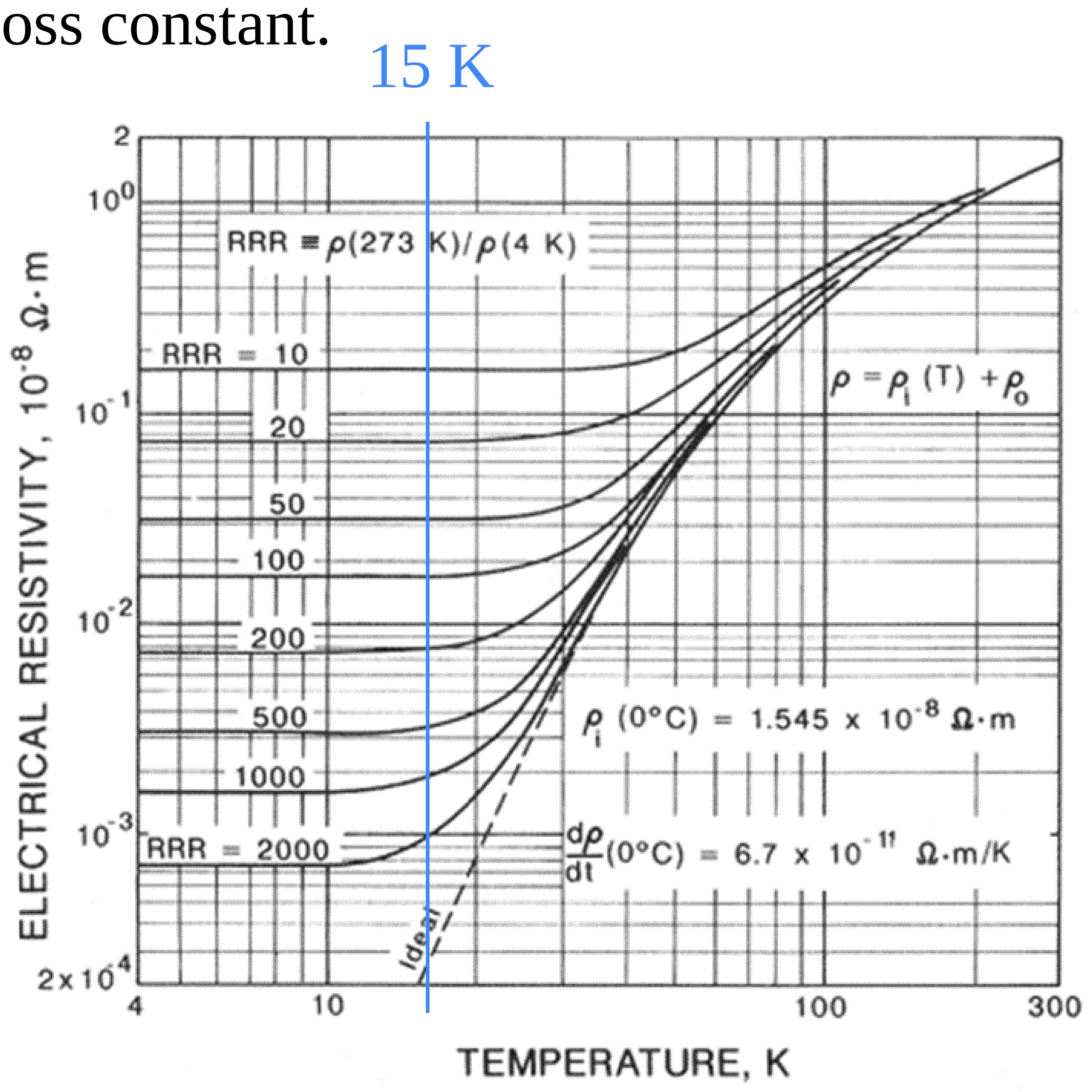
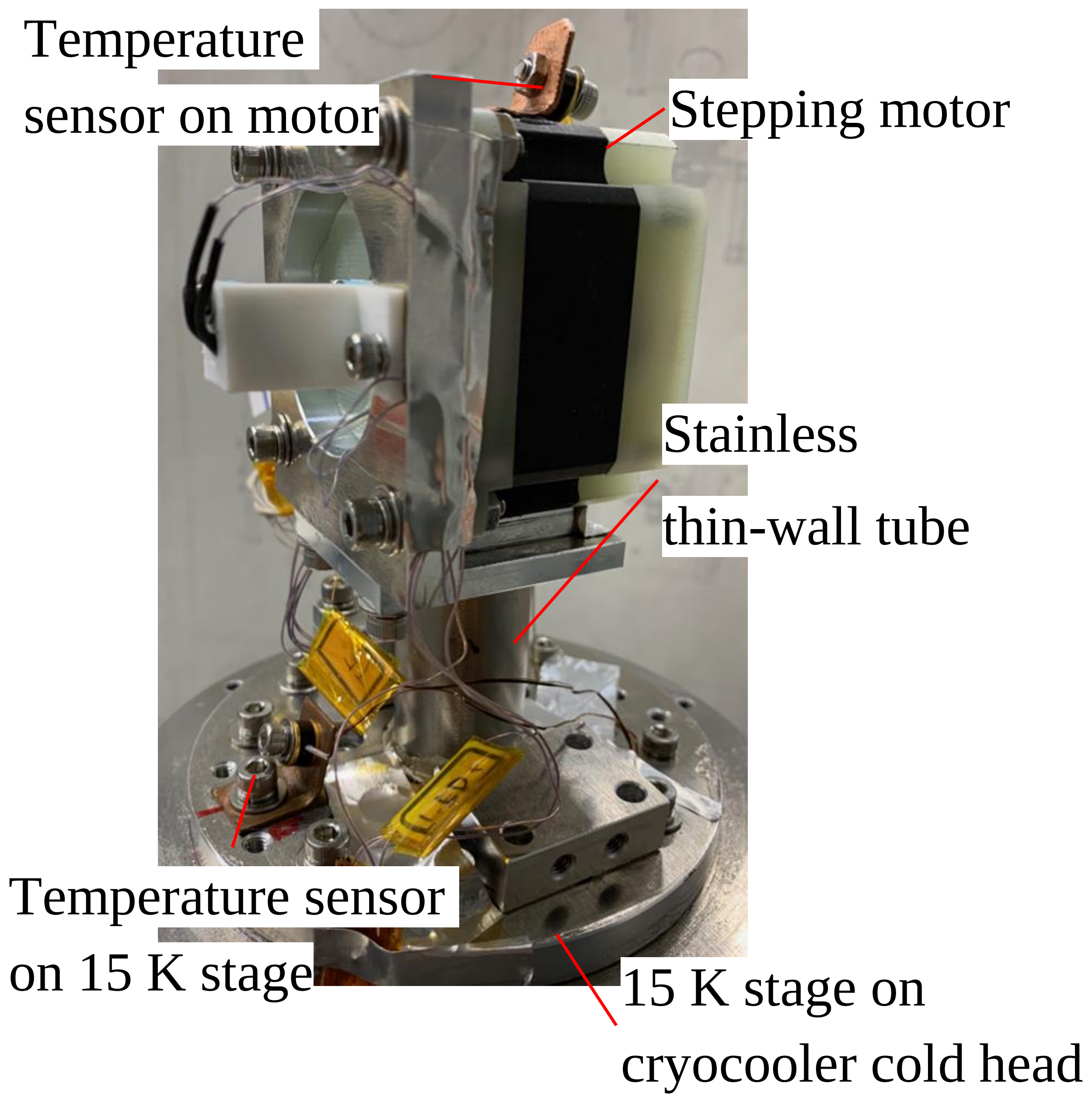


Figure 4. Electrical resistivity of copper as a function of temperature.

Table 1 Original specification of motor

	Specification
Dimensions	56.4 mm x 56.4 mm x L39 mm
Mass	0.45 kg
Step angle	0.9 deg.
Rated current	1.0 A/Phase
Winding resistance	5.4 Ω/Phase @R.T.
Holding torque	0.45 N・m



Measurement Steps (1)

1. Measure each motor coil resistance at the room temperature and 15 K, as shown in **Table 2**.
2. Obtain a relation between a direct current input onto the motor coils and a temperature increase on the motor without rotating the motor.
3. Map a relationship (see **Fig. 7**) between the Joule heat (given the direct current and the coil resistance) and the temperature rise.
4. Rotate the motor with an fixed alternating drive current, 590 mA in amplitude, at the motor rotation frequency and measure a temperature rise of the motor. Using the heat load relationship (**Fig. 7**), we derive a heat dissipation of the rotating motor, given the temperature rise (**Fig. 8**).
5. Caluculate the copper loss with the applied AC current and the coil resistances, asa shown in **Table 3.**

Results

Table 2 Two phase coil resistance

	Conventional coil	High-purity coil
A phase coil resistance	3.83 Ω @ 300K 41.9 mΩ @ 15K	3.80 Ω @ 300K 1.8 mΩ @ 15K
B phase coil resistance	3.83 Ω @ 300K 40.3 mΩ @ 15K	3.83 Ω @ 300K 2.1 mΩ @ 15K

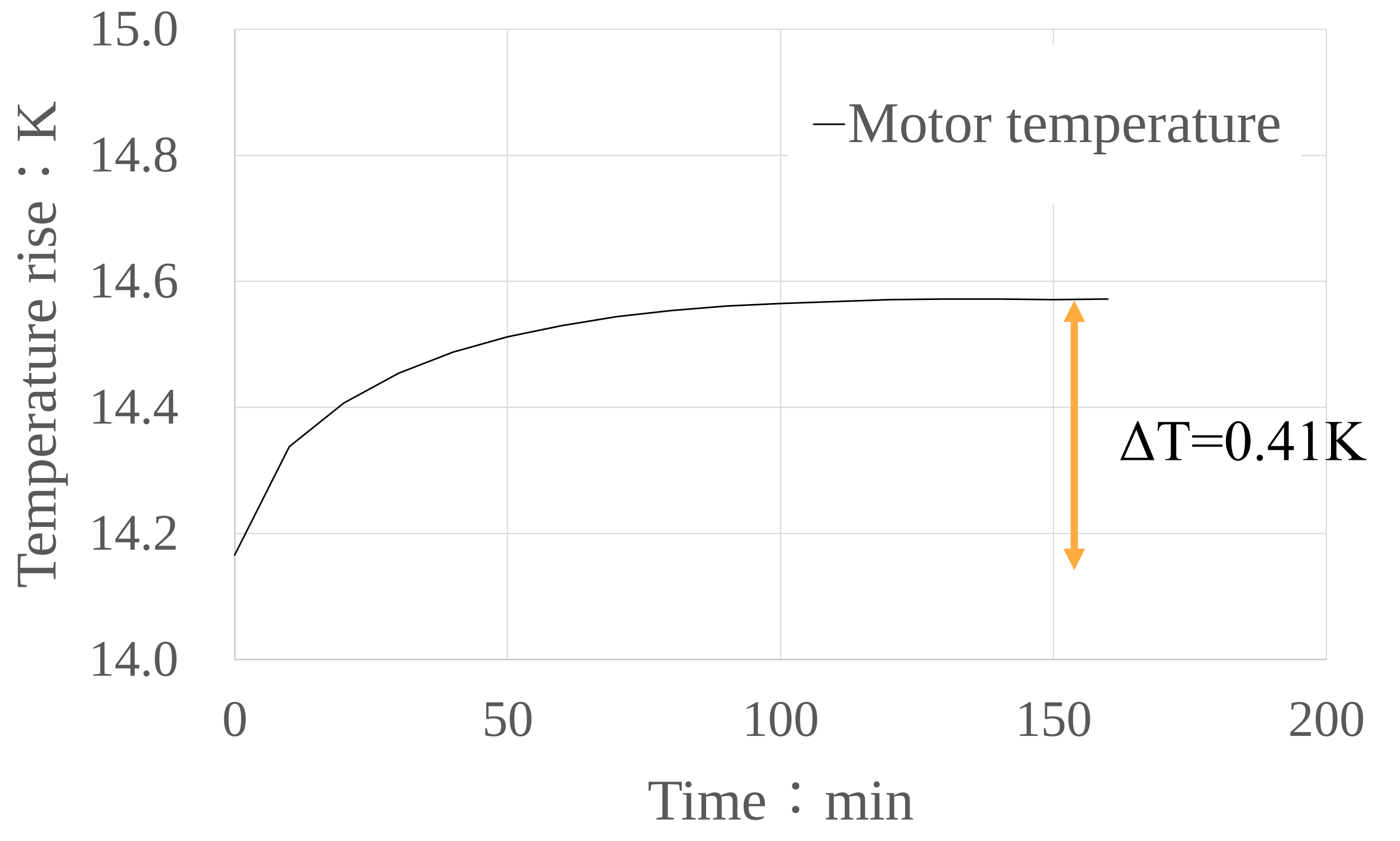


Figure 6. Transient temperature rise on the motor with high-purity coils (non-rotation mode) for 0.98 mW

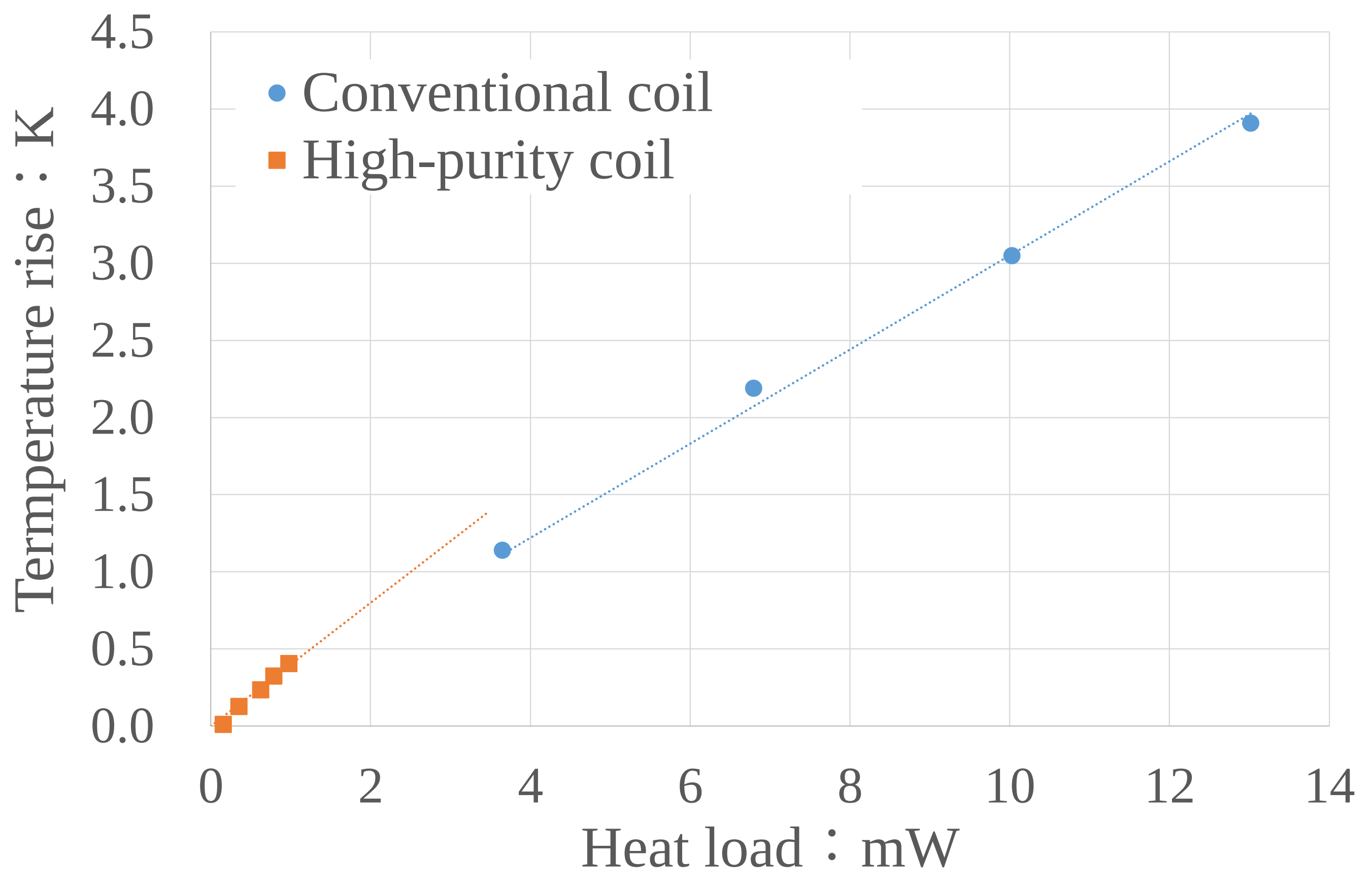


Figure 7. Temperature rises on the motor with various heat load on the motor coil.

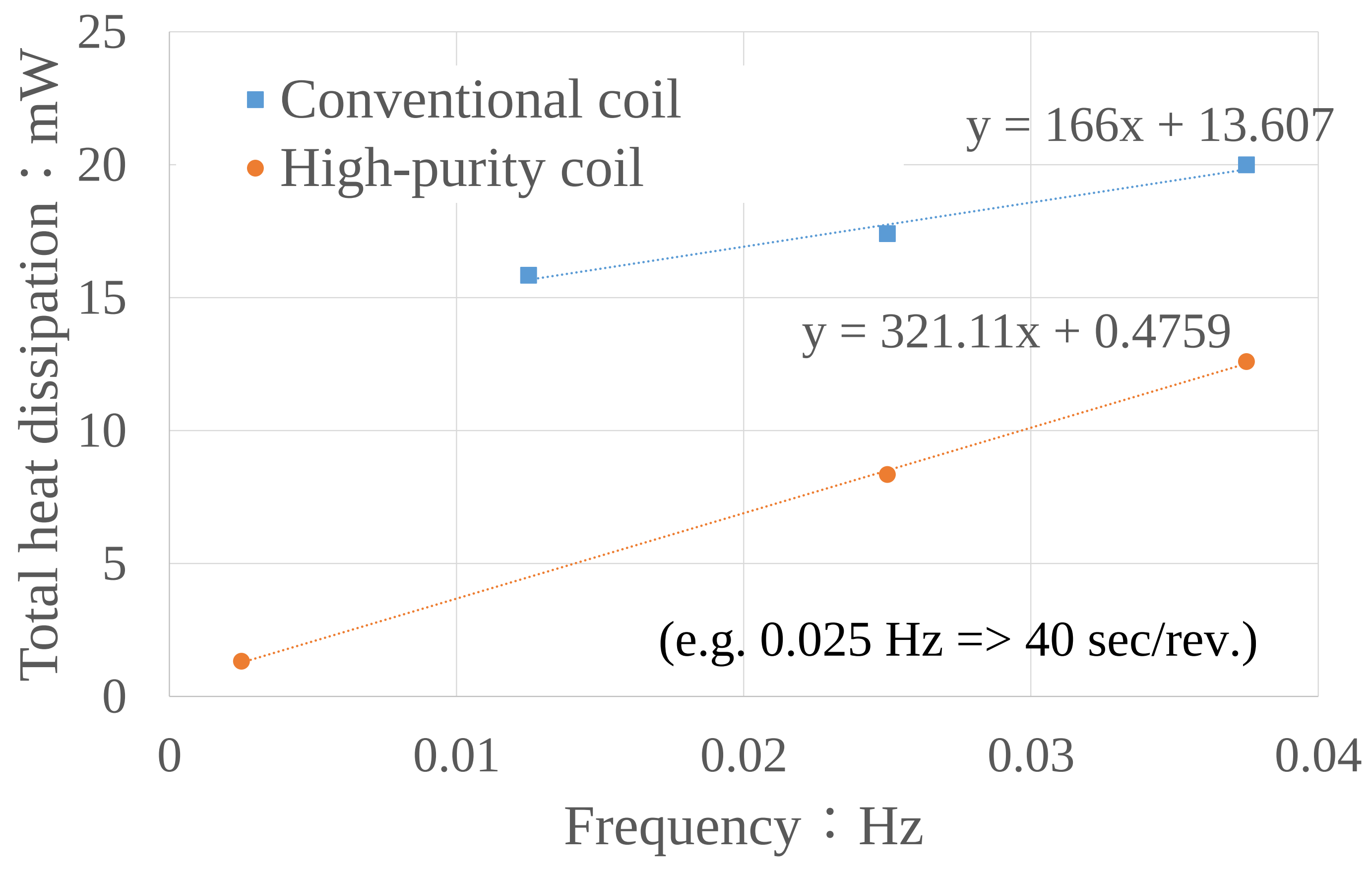


Figure 8. Heat dissipation from the rotating motor to a frequency.

Table 3 Copper loss by Joule heat at 590 mA ac.

	Conventional coil	High-purity coil
Copper loss	14.3 mW	0.68 mW

Measurement Steps (2)

6. Using Eq. (2), we make a graph of (*Mechanical loss+ Hysteresis loss and Eddy current loss / f*) to *the frequency* and you get the mechanical + hysteresis loss constant, "*a*", as the y intercept on the graph.
   Finally, we can separately get a mechanical loss+ hysteresis loss and an eddy current loss.

Table 4. Heat dissipations from the motor with conventional coils

Motor rotation frequency	Total heat dissipation	Copper loss （Joule heat）	Mechanical loss+ Iron loss	Mechanical loss+ Hysteresis loss	Eddy current loss
Hz	mW	mW	mW	mW	mW
0.0125	15.85	14.3	1.55	1.32	0.23
0.025	17.42	14.3	3.12	2.64	0.48
0.0375	20.00	14.3	5.70	3.96	1.74

Table 5. Heat dissipations from the motor with high-purity coils

Motor rotation frequency	Total heat dissipation	Copper loss （Joule heat）	Mechanical loss+ Iron loss	Mechanical loss+ Hysteresis loss	Eddy current loss
Hz	mW	mW	mW	mW	mW
0.0025	1.33	0.68	0.65	0.65	0.01
0.025	8.36	0.68	7.68	6.45	1.23
0.0375	12.61	0.68	11.93	9.68	2.26

Torque measurement

We measured a torque of motor with high-purity coils at a room temperature. Regardless of a motor rotation frequency, the torque measured is 0.12 N m. Since the torque required is more than 0.057 N m, the value sufficiently satisfies the requirement.

Conclusions

1. We reduced the copper loss of the motor with the high-purity coils down to about 20 times smaller than that of the motor with the conventional coils. The eddy current loss was sufficiently small because of very low rotation frequency.
2. It is found that the motor torque with 590 mA ac was about 2 times larger than we expected. Thus, we can reduce the total heat dissipation by reducing the input motor current. Further we have a room for reducing the copper loss by lowering the operation temperatures from 15 K in this experiment down to 5 K in the actual operation. We plan to evaluate these findings in the next experiment at 5 K.

Acknowledgement

This work was supported by JSPS core-to-core program number JPJSCCA20200003.

We also thank Asuka MAEDA for designing the experimental setup and helping the experiment.