Construction and Performance of the NIST-4 Magnet System

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***Abstract*—A watt balance is a promising instrument to realize the unit of mass at the kilogram level. The magnet system is one of the key elements of such an instrument. For the new watt balance currently under construction at the National Institute of Standards and Technology, a permanent magnet system was chosen. We describe the construction of the magnet system, first measurements of the field profile, and techniques that were used to achieve an ideal field profile.**

***Index Terms*—permanent magnet, mass, Planck constant, watt balance, mass metrology**

I. Introduction

A redefinition of the International System of Units, the SI, is impending and might occur as early as 2017. After redefinition, the unit of mass needs to be realized by various means. A group at the National Institute of Standards and Technology (NIST) has been using watt balances to measure a precise value of the Planck constant [1]. Presently, the group is building a new watt balance that will be used to realize the unit of mass in the United States. This watt balance is named NIST-4 [2].

II. Magnet Design and field characterization

The considerations that led to the design of the permanent magnet system described here are given in [3]. While NIST was responsible for the schematic design of the magnet, the detailed design and manufacturing was contracted to Electron Energy Corporation (EEC)[1]. In our design, two samarium cobalt (Sm_2Co_{17}) rings are opposing each other and their magnetic flux is guided by low-carbon steel (AISI 1021) through a cylindrical air gap. The gap has a width of 3 cm and is in total 15 cm long. The central part of this gap is desired to have a radial field uniform along the vertical axis. Short of twelve access holes in each the top and bottom, the gap is entirely enclosed by iron. In order to insert the coil into the air gap, the magnet can be split open such that the top two thirds separate from the bottom third of the magnet. Dowel pins allow us to reproducibly open and close the magnet. Drawings of the magnet and the splitting apparatus are shown in Fig. 1.

After the magnet was assembled for the first time, the radial flux density of the magnet was measured at the manufacturer's facility. Two methods were employed to measure the vertical gradient of the radial flux density: a guided Hall probe and a gradiometer coil. Two setups were used for the Hall-probe method, one built by EEC and the other by NIST. The gradiometer coil consists of two identical coils wound on a single former displaced in the vertical direction z. The two coils are electrically connected in series opposition. Two voltmeters are used to measure the induced voltages as the coil assembly is moved vertically at constant velocity, $v \approx 2\,$mm/s through the magnet. One voltmeter measures the voltage induced in one coil, the other the difference, which can be used to calculate the gradient of the radial flux density along the vertical axis. The results of the measurements are shown in Fig. 2. The variation of the radial flux density along the vertical (z-axis) in the precision gap exceeded 1 mT, hence failing our requirement of a 'flat profile' with $\Delta B_r/B_r < 2 \times 10^{-4}$ by a factor of 10. Based on this measurement, it was decided to

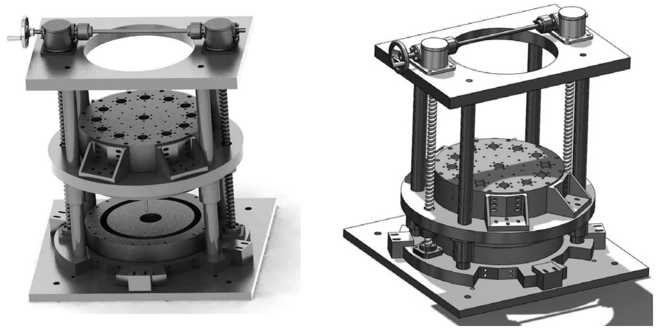

Fig. 1. To install the the coil in the magnet, it can be split open such that the top two thirds of the magnet separate from the bottom third. On the left: magnet in the magnet-splitter with the magnet in the open state. On the right: magnet in the magnet-splitter in the closed state.

[1]Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose

regrind the inner diameter of the outer yoke.

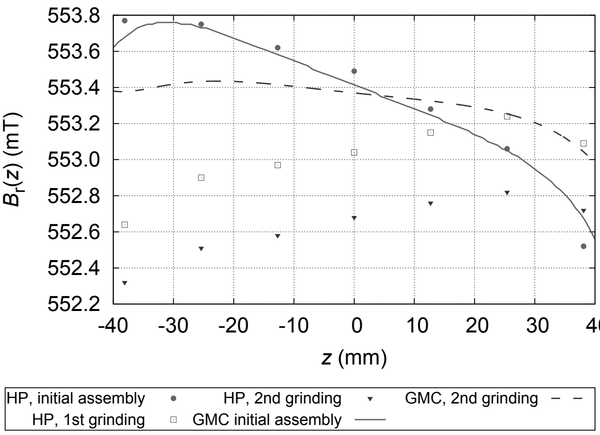

Fig. 2. The points represent data measured with the EEC Hall probe (HP) after initial assembly, the first, and second grinding process. Lines indicate measurements performed with the gradiometer coil (GMC) after initial assembly and after the second grinding. The gradiometer coil readings are 4.2 mT higher. For this plot 4.2 mT were subtracted from the measurements performed with the gradiometer coil.

Since the grinding process did not seem to converge to a flat field profile, other techniques were explored. The first approach was to insert low-carbon steel rods in the inner diameter of the lower Sm_2Co_{17} ring. As can be seen from Fig. 2, the flux density was larger at the lower part of the magnet (negative z values). Inserting steel in the ring changed the slope of the field gradient in the center of the magnet by approximately 1 μT/mm, which was a factor of three smaller than needed. Hence, this strategy was abandoned.

The most effective method to adjust the field proved to be introducing a small air gap between the lower third and the upper two thirds of the magnet. A flat profile is obtained when this additional air gap is about 0.5 mm high. A stable and uniform air gap can be achieved by inserting non-magnetic shim stock pieces at several azimuthal locations. This small air gap increases the reluctance of the lower part of the yoke. Hence, the lower Sm_2Co_{17} ring contributes less flux to the magnetic flux density of the gap. The profile that is obtained with this method as measured with the gradiometer coil is shown as the dashed line in Fig. 3. While this shimming method obtains a flat profile, it has one disadvantage: A small air gap connects the precision air gap inside the magnet to the outside world. Hence the shielding of the magnet is compromised and fields from the outside world can reach into the magnet and perturb the measurement.

We noted that the slope in the center of the gap changed by a few μT/mm every time the magnet was opened and closed. An examination of this effect yielded another shimming strategy. The variability in the slope of the magnetic flux density is caused by non-parallel opening and closing of the magnet. This effectively shifts the working point of the iron at the contact zone on the B-H curve. Even after the magnet is closed, the iron remains in a state of smaller relative permeability due to the hysteric behavior of the B-H curve. Hence, in the closed state this part of the yoke conducts the magnetic field less effectively and the flux in the gap is lower. By opening and closing the magnet slightly more than 1 mm in a tilted fashion at different azimuthal positions, the iron is driven to a state with less relative permeability along the entire circumference. This process is repeatable and we were able to reproduce an almost identical field profile several times.

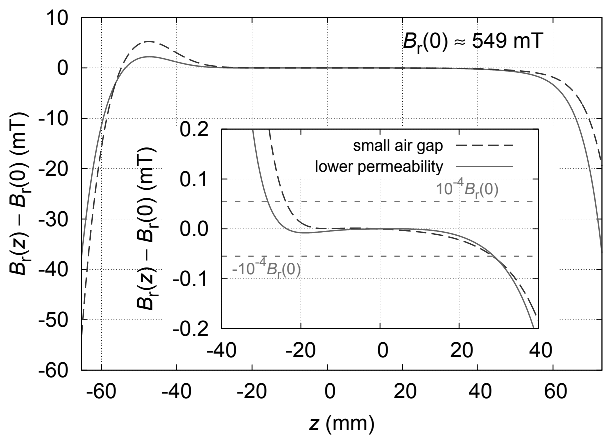

Fig. 3. The radial flux density as a function of vertical position. The inset shows the central region magnified such that the total size of the vertical axis extends $\pm 4 \times 10^{-4}$ around the value at $z = 0$. Two shimming methods lead to a similar profile: introducing a small air gap (dashed line) and reducing the relative permeability of the iron (solid lines).

III. Conclusion

The NIST-4 magnet has been successfully built. Initial measurements of the basic properties of the magnet were carried out at NIST [4]. Dedicated gradiometer coils were built to measure the gradients of the magnetic flux density in the precision air gap. After delivery, it was found that the magnetic field profile could be further improved by two shimming methods. Using those techniques, the field profile could be changed to have a nearly vanishing derivative with respect to z at the symmetry plane of the magnet. The magnetic flux density stayed within $\pm 10^{-4}$ of its value in the center over a travel range of 6 cm. It was found that the radial dependence of the magnetic flux density follows a $1/r$ dependence closely, and we expect any relative systematic error due to geometry changes of the coil to be smaller than 2×10^{-9}.

References

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