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A MEASUREMENT SYSTEM FOR PROTON GYROMAGNETIC RATIO DETERMINATION AS A BASIS FOR A MAGNETIC FLUX DENSITY STANDARD

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Abstract − The proton gyromagnetic ratio (γ'_P) plays a fundamental role in achieving highly accurate magnetic-field measurements. At the KRISS complex for the determination of the proton gyromagnetic ratio, we have improved a magnetic-field standard based on the value of γ'_P and related techniques. The standard for measuring DC magnetic flux density is intended to cover the range from 20 μT to 2.5 T, with an uncertainty ranging from 4×10^{-6} to 6×10^{-5} T.

Keywords: Magnetic flux density standard, proton gyromagnetic ratio.

1. INTRODUCTION

The proton gyromagnetic ratio in water, γ'_P, represents the physical connection between the magnetic field and the Zeeman magnetic-resonance frequency for a system of fundamental physical constants. The proton gyromagnetic ratio γ'_P is one of the basic constants for establishing the standards of the electromagnetic SI units [1]. As well as its role in fundamental metrology, γ'_P plays an important role in magnetic measurements, where it serves as a conversion coefficient for proton-magnetic-resonance instruments. It is also the basis for the determination of the gyromagnetic ratios of other particles used for precision magnetic measurements [2]. Quantum interconnection between magnetic flux density (B) and the magnetic resonance frequency of the proton (ω_P) is defined by the well-known ratio:

$$\omega_P = \gamma'_P \cdot B \tag{1}$$

The value of γ'_P has recently been measured at KRISS (Korea Research Institute of Standards and Science) in collaboration with VNIIM (D. I. Medeleyev Institute for Metrology) as $2.675\,154\,18 \times 10^8\ \mathrm{s^{-1}T^{-1}}$ with an uncertainty of 0.18×10^{-6} [3]. The main distinguishing feature of the measuring system we designed is the application of the method of ^{4}He atomic magnetic resonance (AMR). This is based on optical-pumping polarization using metastable exchanges with polarized cesium atoms, instead of the usual proton magnetic resonance [3]. The ^{4}He-AMR technique has important advantages for low fields, not only in comparison with proton nuclear magnetic resonance (NMR), but also with ^{3}He-NMR. The AMR frequency is hundreds of times higher than that for NMR, and the more effective optical method of AMR signal monitoring provides higher relative accuracy in determining the AMR frequency.

Measurement of γ'_P can be applied to the reproduction of the magnetic field unit, the tesla (T), over a wide magnetic flux-density range. This is relevant to studies of the physical nature of Earth's magnetism in geophysical research associated with the natural time–space distribution of parameters of a magnetic field on the Earth's surface. This knowledge can be applied to the discovery of mineral resources, and to searches for hidden technical objects and the determination of their magnetic parameters. Such measurements are important for defense studies as well as in other spheres.

In this paper, we present the standard systems and their applications for reproduction and measurement of magnetic flux density using the technique of γ'_P-determination.

2. STANDARD SYSTEM

The measurement standard of KRISS includes an AMR helium (^{4}He) magnetometer, a proton teslameter, a precision quartz solenoid, three-component and one-component Helmholtz coils, electromagnets , and an automatic system for compensating for Earth's magnetic field.

The basis of the standard AMR magnetometer is ^{4}He metastable 2^3S_1 spin polarization with high-frequency heating of the plasma by spin-exchange collisions with optically pumped ^{133}Cs atoms [4-5]. The basic metrological examination of this method was made in [6].

The latest experimental determination of the ^{4}He atom's gyromagnetic ratio using this method was realized by the authors of this paper and reported in [3]. The result is:

$$\gamma_{^4He} = 1760.78819 \times 10^8\ \mathrm{s^{-1}T^{-1}}\ (0.18 \times 10^{-6}) \tag{2}$$

The values of $\gamma_{^4He}$ and γ'_P quoted above are accepted in the present work as conversion coefficients for the standard He-Cs and proton magnetometers.

While the He-Cs standard magnetometer was used for direct transfer of tesla values in the range 20 μT to 1.2 mT, the solenoid is the source of a stable homogeneous magnetic field, and serves as a standard measure of the dimension T/A for the calibration of the magnetic flux-density coils, and as an instrument for comparison of the magnetometers. Calibration of the magnetic flux-density coil was performed using the ratio of two fields measured by the He-Cs magnetometer: one generated by the solenoid and the other by the coil to be calibrated with identical currents.

In the range 1 – 25 mT, a system of Helmholtz coils was used; for fields above 40 mT, the standard is based on NMR. A commercial product, MetroLab PT-4025, was used.

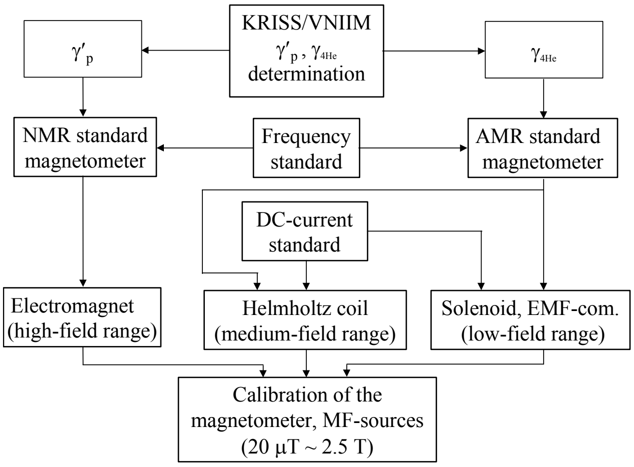

Fig. 1. Traceability of the magnetic flux density unit standards at KRISS.

Figure 1 shows the traceability chain for transference of the magnetic flux density unit. The standard serves to calibrate the DC magnetometers, teslameters, magnetic flux-density coils and support experiment related to research involving magnetic fields in the range of 20 μT to 2.5 T.

2.1. Low-filed standard (below 1.2 mT)

Figure 2 shows a block diagram of the standard measuring system. It consists of a He-Cs-AMR magnetometer, a precision solenoid, an AMR current-stabilizing and measuring set, and apparatus for compensation of the EMF [7].

We use a solenoid of enameled copper wire wound with a 1-mm pitch on a fused silica former having a 10.1-cm radius and length of 0.938 m. The precision magnetic field below 1 mT is generated with the dimension of a solenoid and the current that is passing through the solenoid in the zero-field space formed by compensation for any EMFs in a nonmagnetic facilities [8]. To improve the field uniformity in the solenoid, we have developed a multi-stage system that has allowed us to ensure high homogeneity of the field with a single current [7]. The precision solenoid is placed at the center of the three-component EMF-compensation-coil system. For reproduction of low DC magnetic field, the external field (EMF) is removed

The EMF compensatory Helmholtz coil consists of two coil systems (the main and auxiliary), each of which has three orthogonal coil components with diameters of about 1.8 m and 0.9 m.

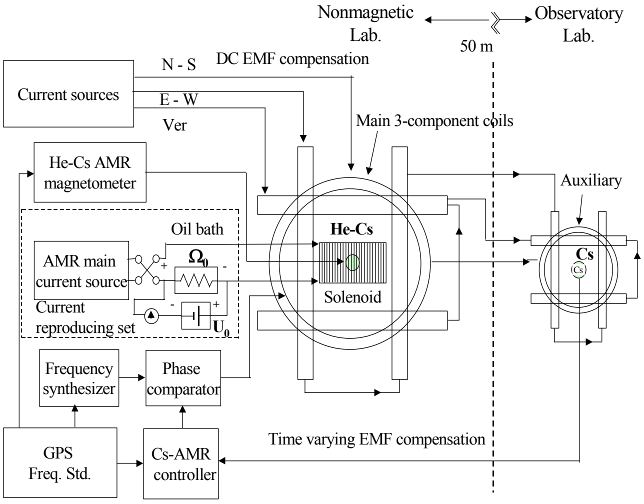

Fig. 2. Block diagram of the low magnetic flux density standard system (below 1.2 mT).

The pairs of main and auxiliary coil windings for each component have identical coil constants, are connected serially, and use separate current sources. While the main AMR current source was used for the standard MF generation by the solenoid, three additional current sources provided compensation of each permanent EMF component. The Cs-AMR field-controller is connected to one of the 3-axis Helmholtz coil windings. This system automatically cancels out EMF variations in the solenoid axis direction. Variations of the EMF are automatically compensated for, within 0.1 nT/h, by a Cs-AMR field controller. The main current source supplying the solenoid is an AMR-based stabilizing system [9-10] with an instability between 1×10^{-7} and 1×10^{-6} in the range 1 A to 0.1 A.

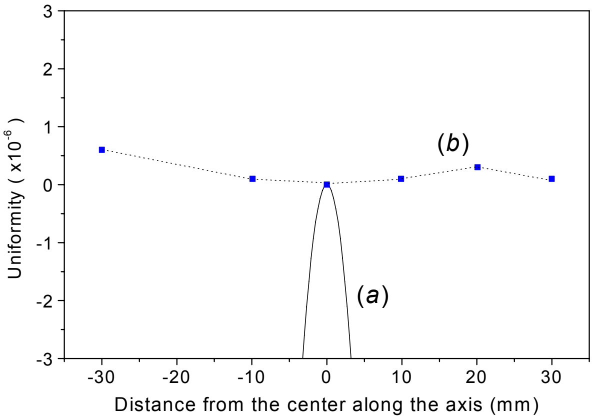

Fig. 3. Field distribution of simple solenoid (a) and high uniform field solenoid (b) corrected by multistage method.

The solenoid reproduces a DC field that is uniform to better than 3×10^{-7} within ± 2 cm around its center (Fig. 3) compared with a non-uniformity of 1×10^{-4} for an uncorrected, simple solenoid. The experimentally measured coil constant and temperature coefficient of the solenoid are 1.2310596×10^{-3} T/A (25 °C) and 3.8×10^{-7}/°C respectively

[7]. The stable, uniform magnetic field is maintained in the range 0.02 – 1.2 mT with an uncertainty of (4 – 21) × 10^{-6} with (k=2) (TABLE I).

TABLE I. Uncertainty estimation.

Items	Uncertainty, 10^{-6}	
	0.02 mT	1.2 mT
1. He-Cs magnetometer	0.5	0.5
2. Solenoid magnetic field uniformity	0.3	0.3
3. Main current stability	1.0	0.1
4. EMF-compensation coil Uniformity	2.0	0.1
5. Stability of the compensated magnetic field	10.0	2.0
Expanded uncertainty (k=2)	**20.6**	**4.2**

2.2. Medium-field range system

Magnetic flux density in the range 1 mT to 25 mT is reproduced by a Helmholtz coil. As Fig. 4 shows, the system consists of two coaxial Helmholtz coils, a current source, a standard resistor, a precise voltmeter, and a computer. The axes of the Helmholtz coils are oriented perpendicular to the EMF. One of them is used for EMF compensation in the coil-axis direction, and the other (main) is used to reproduce the calibrating magnetic field.

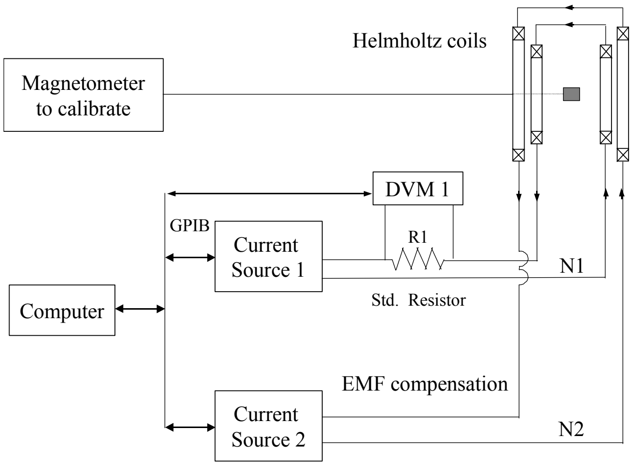

Fig. 4. Block diagram of the magnetic field standard for the range of 1 mT – 25 mT.

The dimension of T/A for Helmholtz coil-constant transfers from the standard described above low-field standard by means of standard solenoid and He-Cs magnetometer.

A current passing through the coil winding is reproduced by measuring the voltage across the standard resistor. Computerization of the magnetic field monitoring reduces the calibration time.

The uniformity of the reproduced magnetic field was improved by correction of an inaccuracy in the coil manufacture by shunting of one of the section windings, and correcting the distance between sections. The constant of the main Helmholtz coil is 6.42082 mT/A (25 °C) with an uncertainty of 6 × 10^{-5} (k=2).

2.3. High-field range system

The parameters of the standard system in the high-field range (from 0.04 T to 2.5 T) are determined using proton (in water) NMR with induced precession. This system consists of an NMR magnetometer, an electromagnet, a precision current stabilizing and measuring devices, and a computer (Fig. 5).

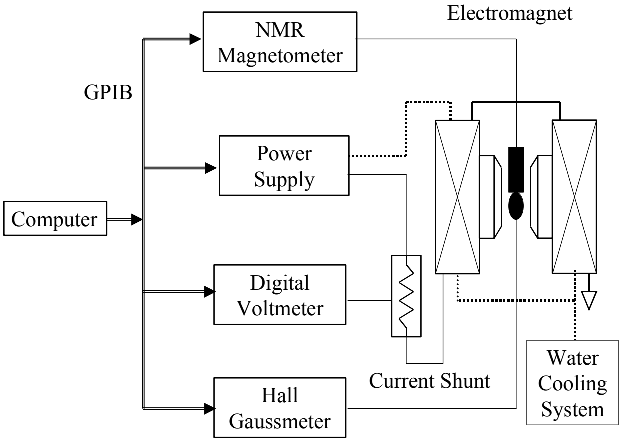

Fig. 5. Block diagram of the standard system for (0.04 – 2.5) T range.

The system is computerized to monitor magnetic field variations and save time for the calibration. The magnetometer was calibrated by determining the dependence of the magnetic resonance frequency on the parameters formatting the NMR signal, and through an independent method of measuring the NMR frequency.

The NMR teslameter and the highly uniform electromagnet reproduce a magnetic flux density within ± 1 cm from the center of the electromagnet working volume in the range of 0.04 – 2.5 T with an uncertainty (1 – 5) × 10^{-5} (k=2).

3. CONCLUSION

Theoretical and experimental research into γ'_p reported here provides an essential value for both fundamental and practical metrology of magnetic field measurements. The atomic-resonance-based current stabilizer and the compensation system for Earth's magnetic field are themselves of interest for metrology applications in electromagnetic instruments. The measuring complex we developed allowed us to reduce the uncertainty in the reproduction of the tesla at KRISS by about 100 times at low field values. It also allowed us to create a new primary standard for the magnetic flux-density unit, which can be used for calibration of any industrial-standard magnetometers. Calibration time was saved by automation using computer control.

For other laboratories, the standard allows reproduction of the magnetic flux density in the range 20 μT to 1.2 mT with (4 – 21) × 10^{-6} uncertainty with a coverage factor of 2.

The magnetic flux-density unit is maintained in the range of 40 mT to 2.5 T and 1 to 25 mT, respectively, with an uncertainty of (1 - 5) × 10^{-5} with a coverage factor of 2, using an NMR system and a Helmholtz coil.

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