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Development of a center field compensation system for high-temperature superconducting magnets using PID control based on auto-tuning

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Abstract

This paper proposes a center field compensation system using PID control with auto-tuning to improve the temporal stability of high-temperature superconducting (HTS) magnets. The proposed control system is designed to mitigate magnetic field drift induced by screening currents, as well as fluctuations resulting from power supply ripple in HTS magnets. Various auto-tuning techniques were implemented and evaluated to optimize the controller gains, thereby improving the performance of the field compensation system. A background coil, simulating a HTS coil, and a central magnetic field compensation coil were fabricated, and experiments were carried out to compare the performance of each auto-tuning method based on Settling Time and %Overshoot. Experimental evaluation of the compensation coil demonstrated that the Cohen-Coon tuning method is the most effective for central magnetic field compensation. Current distortions, replicating drift caused by screening currents in HTS magnets and fluctuations from the power supply ripple, were applied to the background coil. Using the proposed method, the central magnetic field was successfully compensated, significantly enhancing the temporal stability of the magnet. After successful validation of the auto-tuning-based central magnetic field compensation technique, a Z0 compensation coil for the 400 MHz (9.4 T) HTS NMR magnet was designed and fabricated. Applying the proposed system to HTS NMR magnets is expected to significantly enhance the temporal stability of the magnetic field.

Keywords: center field compensation system, HTS magnet, PID control, auto-tuning, temporal stability

1. INTRODUCTION

High magnetic fields are fundamental to NMR and MRI systems, as they improve image resolution and sensitivity, enabling higher-quality imaging and the analysis of increasingly complex protein structures [1]. Therefore, high-temperature superconducting (HTS) wires, which can maintain relatively higher critical currents compared to low-temperature superconducting (LTS) wires even under high magnetic fields, are well-suited for high-field NMR and MRI applications [2]. Consequently, many research institutions are actively pursuing the development of high-field systems above 1 GHz (equivalent to a magnetic field of 23.5 T) employing HTS wires [3-7].

However, HTS magnets suffer from long-term field drift caused by screening currents, as well as short-term field drift caused by power supply ripple in driven mode, resulting in decreased temporal stability of the magnetic field [8-9]. In NMR and MRI systems, which require spatially homogeneous and temporally stable magnetic fields, such magnetic field instability degrades the quality of measurement and analysis. Therefore, improving the temporal stability of the central magnetic field is essential.

In this paper, we propose a PID control-based center field compensation system to enhance the temporal stability of HTS magnets [10]. Applying optimal control gains is crucial for fast and accurate PID control, and auto-tuning methods were employed to achieve the optimization of the control gains. Compared to existing approaches, the proposed center field compensation system offers significant advantages by automatically optimizing control gains to improve temporal stability [11]. Through experimental evaluation, the most suitable tuning method for optimizing control gains was identified. Then, the feasibility of the proposed method was validated by controlling the current of a central magnetic field compensation coil, installed within a background coil intentionally destabilized to simulate the effects of screening currents and current ripple from power driven mode.

The proposed method demonstrated its effectiveness in compensating the central magnetic field under various conditions and proved its applicability to large-scale HTS magnet systems, where the temporal stability of the central magnetic field may deteriorate due to screening currents and other factors. The proposed method is expected to be applied to the central magnetic field compensation of a 400 MHz-class HTS NMR magnet, and the design and fabrication of the compensation coil are also currently in progress.

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2. CENTER FIELD COMPENSATION METHOD FOR HTS MAGNETS

2.1. Concept of the center field compensation employing PID Control

In this study, a center field compensation system was implemented using PID control, and the overview of the method is shown in Fig. 1. The target magnetic field value is input as the Set Point (SP), and real-time magnetic field data, denoted as Process Variable (PV), are obtained by measuring the voltage with a nanovoltmeter (NVM) while maintaining a current of 0.1 A through the Hall sensor. The difference between the SP and PV is calculated, then, the control gain determines the input to the plant. The output (coil current) from the plant is then continuously applied the compensation coil to regulate the PV, thereby facilitating its convergence toward the SP. The control technique is continuously repeated to ensure that the measured PV achieves alignment with the SP.

2.2. PID Gain Optimization through Auto-tuning

PID control is a widely used method for stabilizing systems, and optimal control gains are essential for achieving fast and accurate control. The process of automatically calculating these optimal control gains is called "Auto-tuning" and there are several methods available for this purpose.

In this study, we investigated four auto-tuning methods: the Ziegler-Nichols (Z-N) Method, the Cohen-Coon Method, the CHR Method, and the IMC Method [12].

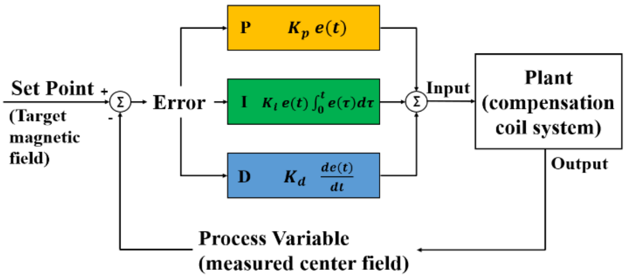


Fig. 1. Concept of the PID control used in the center field compensation system.

TABLE 1
OPTIMAL DESIGN RESULTS OF EACH COIL USING GA.

Parameters	Background Coil	Compensation Coil
Inner Radius	15 [mm]	3.5 [mm]
Outer Radius	22.2 [mm]	5.9 [mm]
Axial Height	19.2 [mm]	3.6 [mm]
Radial Thickness	7.2 [mm]	2.4 [mm]
Operating Current (I_{op})	2 [A]	0.5 [A]
Number of Turns (R)	12 turns	4 turns
Number of Turns (Z)	32 turns	6 turns
Coil Length	44.15 [m]	2.39 [m]
Magnetic Field @ I_{op}	230.8 [G]	15.1 [G]

These four methods determine optimal control gains in different ways, and we analyzed the features of each method and compared their performance using the coil system.

The Z-N Method determines control gains based on two main constants derived from the dynamic characteristics of the control system: the delay time (L) and the time constant (T). This method has the advantage of finding optimal control gains easily, but it may lead to overshoot or prolonged response times [13].

The Cohen-Coon Method determines control gains by modeling the system's step response as a first-order lag system. This method calculates the gains using three main parameters: the time constant of the first-order response (τ_m), the dead time (τ_d), and the steady-state output value divided by the input step change (K). This method provides a more accurate model of the system compared to the Z-N Method, but the tuning process can be more complex [14].

The CHR Method is an improved version of the Z-N Method, focusing on enhancing response speed and reducing overshoot. It uses the same delay time (L) and the time constant (T) as the Z-N Method to calculate control gains, but applies different formulas to achieve better performance [15].

The IMC method designs the controller based on a mathematical model of the system to determine optimal PID gains. This approach optimizes the controller design while considering stability and disturbance rejection [16].

Each of the four methods has its own strengths and weaknesses, and the most suitable method varies depending on the system. Therefore, it is important to experimentally apply these methods to the target system to determine the most appropriate one for actual control.

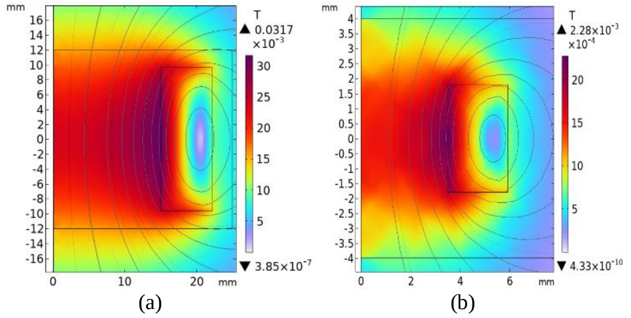
3. IMPLEMENTATION OF A CENTER FIELD COMPENSATION SYSTEM USING AUTO-TUNING TECHNIQUES

3.1. Overall System Design and Configuration

In this study, a small scale background coil was designed using copper coils to simulate the temporally unstable HTS magnets. The background coil and Z0 compensation coil were designed using the Genetic Algorithm (GA) function in MATLAB [17-18].

In the design process, the number of R turns and Z turns of the coil were set as design variables, and nonlinear constraints were established to ensure that the total length of the coil remained below a certain value. Within these constraints, the objective function was set to maximize the central magnetic field of the coil, and the optimal design of each coil was derived accordingly. It should be noted that, the coils of the prototype system, developed to validate the central field compensation system, were optimized solely to maximize the magnetic field strength.

The design results of each coil wound with 0.6 mm copper wire are presented in Table 1 and the design was verified through electromagnetic analysis using COMSOL. The verification results are shown in Fig. 2, confirming that the designed coil meets the required magnetic field characteristics.



(a) (b)

Fig. 2. Electromagnetic analysis results of the designed coil using COMSOL: (a) background coil, (b) Z0 compensation coil.

The background coil and Z0 compensation coil were wound with copper wire of 0.6 mm thickness on a Poly Lactic Acid (PLA) bobbin. The central magnetic was measured using a Lakeshore HGA-3030 axial Hall sensor. The measured values were then displayed using a Keithley 2182a NVM. The NVM and the control computer communicate data using the GPIB protocol. When a measurement command is sent to the NVM via LabVIEW, it takes approximately 70 ms (sampling time) for the measured Hall sensor voltage to be returned to the LabVIEW program.

An overview of the center field compensation system and a flowchart representing the operational principle are shown in Fig. 3 and Fig. 4, respectively. At first, the field compensation system derives the control gain using the given auto-tuning method. Then, the system precisely measures the central magnetic field of the background coil, which varies in real time, calculates the difference from the target value, and inputs this value into the auto-tuned PID controller to regulate the compensation coil current.

3.2. Selection of the optimal auto-tuning method suitable for current control in the compensation coil system

Settling Time, which relates to how quickly the system reaches the target value and %Overshoot, which indicates how much the system temporarily overreacts before settling at the desired target value, are key indicators to evaluate control effectiveness of the four tuning methods. The formulas for each parameter are as follows:

- Settling time: The time required for the system output to remain within 2% (or 5%) of the final value

- %Overshoot: $\frac{Maximum\ output - Target\ output}{Target\ output} * 100$

After applying the four auto-tuning methods to the field compensation coil system, control performance was evaluated by measuring the settling time and %overshoot 10 times for each method. The results are presented in Table 2.

As shown in Table 2 the Cohen-Coon method was determined to be the most effective in yielding optimal control gains, with the lowest %Overshoot of 0.3591% and the fastest settling time of 5.9 seconds. A lower %Overshoot reduces unnecessary oscillations when reaching the target value, thereby enhancing system stability, while a shorter settling time indicates faster convergence to the target value, reducing the overall response time. Accordingly, this study employed the Cohen-Coon method to derive the control gains for controlling the compensation coil current.

3.3. Experimental Results of the center field compensation using the proposed method

To simulate the field drift due to the screening current of HTS magnets, the baseline current of 0.02 A applied to the background magnet was artificially increased by a specific proportion. Additionally, random values were added or

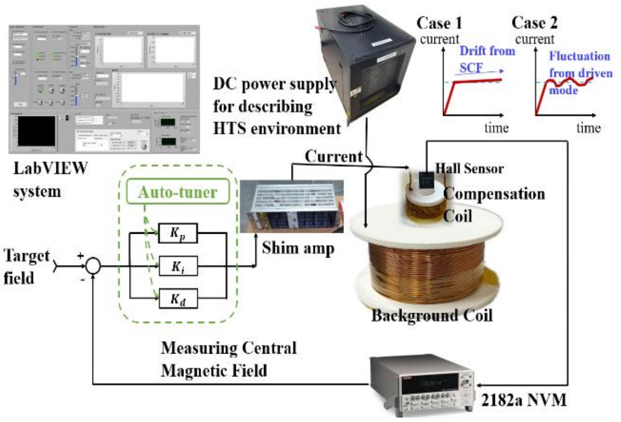


Fig. 3. Overall schematic of the center field compensation system.

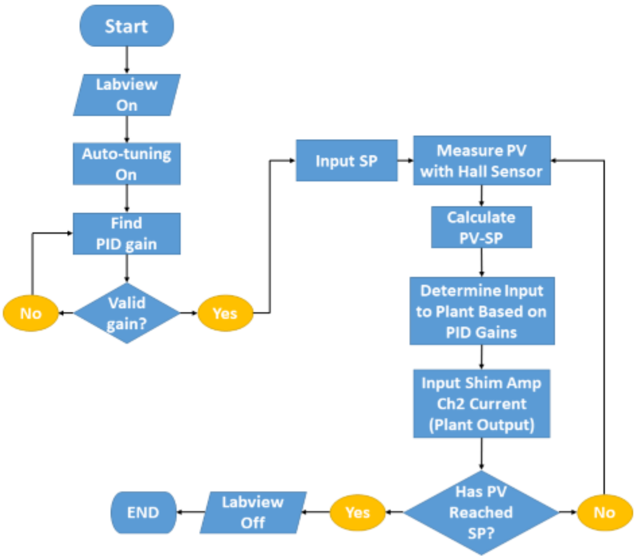


Fig. 4. Operating flowchart of the center field compensation system.

TABLE 2
CONTROL PERFORMANCE RESULTS WITH RESPECT TO THE AUTO-TUNED METHOD.

Auto-tuning	Comparison	Average
Ziegler-Nichols	%Overshoot	0.7261 %
	Settling Time	54.3 s

Cohen-Coon	%Overshoot	**0.3591 %**
	Settling Time	**5.9 s**
CHR	%Overshoot	0.7211 %
	Settling Time	46.9 s
IMC	%Overshoot	0.6754 %
	Settling Time	12.4 s

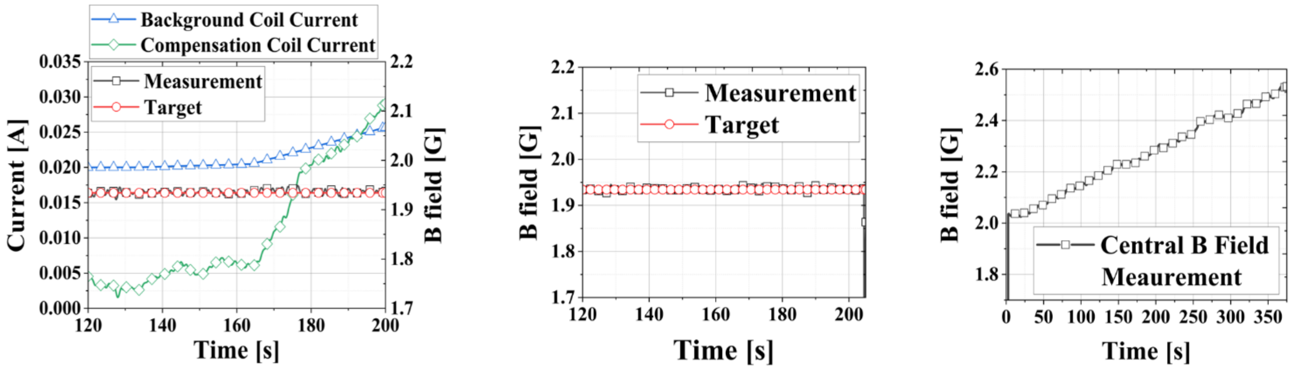
subtracted from the background coil current to simulate the current fluctuation of the DC power supply in driven mode. Following the installation of the proposed field compensation system within the background coil, its control performance was evaluated through experimental testing. The results of compensating for the central magnetic field in the case of simulating drift due to Screening Current-induced Field and current fluctuation of the DC power supply in driven mode are shown in Fig. 5(a) and Fig. 6(a), respectively.

Fig. 5 represents the results of the compensation coil control under simulated field drift conditions. Specifically, Fig. 5(a) presents the background coil current, compensation coil current, target magnetic field, and measured magnetic field during the control process using the control system. Fig. 5(b) presents a magnified view of the magnetic field during the control process. When compared with the uncontrolled magnetic field drift shown in Fig. 5(c), the effectiveness of the control system becomes clearly evident.

Similarly, the experimental results of the compensation coil control under conditions considering magnetic field fluctuations are presented in Fig. 6. In particular, Fig. 6(a) presents all measurement data obtained during the compensation coil control process, while Fig. 6(b) presents a magnified view highlighting the measured field data. Fig. 6(c) shows the magnetic field fluctuations in the absence of the compensation coil current, revealing significantly larger variations in the magnetic field compared to those shown in Fig. 6(b).

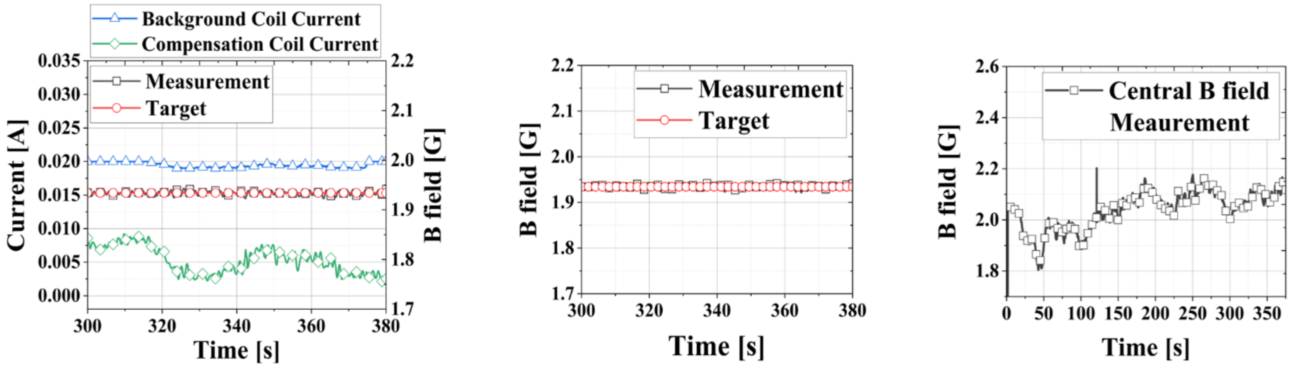
To evaluate the performance differences in magnetic field compensation based on control gain, the central magnetic field correction results were compared between the gains determined through Cohen-Coon method and those derived using the Z-N method as shown in Fig. 7. Similar to the results shown in Table 2, which presents the settling time and percent overshoot results based on control gains, Fig. 7 demonstrates that under field drift conditions, the Cohen-Coon method achieves significantly better central magnetic field correction performance compared to the Z-N method.

These results demonstrate that the field compensation



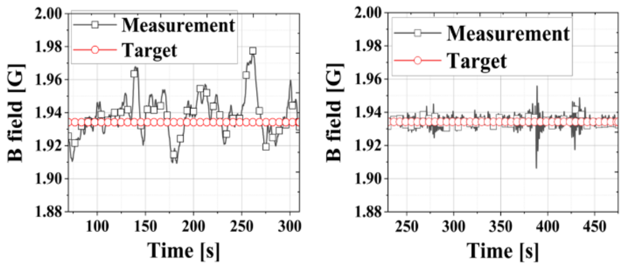
(a) (b) (c)

Fig. 5. Experimental results of the compensation coil current control under the conditions considering field drift caused by screening currents: (a) all measurement data obtained during the control process, (b) magnified results of the magnetic field during the control process, (c) magnetic field results in the absence of control.



(a) (b) (c)

Fig. 6. Experimental results of the compensation coil current control under assumed current fluctuation conditions: (a) all measurement data obtained during the control process, (b) magnified results of the magnetic field during the control process, (c) magnetic field results in the absence of control.



(a) (b)

Fig. 7. Results of central magnetic field compensation experiments using control gains obtained by (a) Z-N Method, (b) Cohen-Coon Method.

system, using control gains obtained through auto-tuning, effectively and accurately maintains the central magnetic field at the target value. This suggests that the proposed system can maintain the central magnetic field of HTS magnets stably over the long term, providing the necessary environment for high-precision analysis and high-resolution imaging.

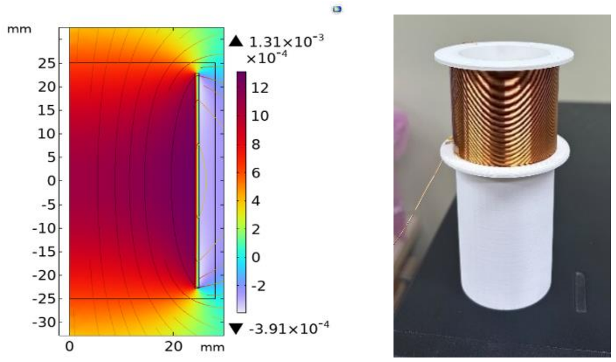
4. APPLICATION OF THE PROPOSED COMPENSATION COIL CONTROL TECHNIQUE FOR 400 MHZ (9.4 T) HTS NMR MAGNETS

The field compensation system using the small scale coils system was designed and evaluated to verify the control performance considering HTS magnet environments: field drift from screening currents and current fluctuations from the power supply driven mode. To apply the proposed control system to a 400 MHz HTS NMR magnet installed at Korea Basic Science Institute (KBSI), a large scale Z0 compensation is required. The large scale Z0 compensation coil for the 400 MHz HTS NMR magnet was designed using the Genetic Algorithm (GA) function in MATLAB.

To maximize the performance of the Z0 component coil, the objective function was set to the proportion of the Z0 component in the overall harmonic components [19]. The inner radius of the winding was set to 24 mm, and a 0.3 mm copper wire was employed. Nonlinear constraints were applied to ensure design feasibility, including limiting the maximum central magnetic field for compensation to less than 20 G and the total winding length to less than 70 m.

The design variables were defined as the number of turns in the radial (R) and axial (Z) directions. The design results are presented in Table 3 and the electromagnetic analysis results using COMSOL are shown in Fig. 8(a).

Based on the design, a Z0 compensation coil was wound onto a PLA bobbin sized to fit the room-bore size of the 400MHz NMR magnet. Fig. 8(b) shows a photograph of the fabricated Z0 compensation coil. When applying to the 400 MHz HTS system, it may be necessary to perform NMR measurements of the actual sample and magnetic field compensation simultaneously. Therefore, a small NMR sample wrapped with an RF coil for the field compensation will be placed just below the main NMR sample for actual measurements. The NMR spectrum of this small NMR sample acquired by the KBSI magnetometer system will be used to measure the central magnetic field in real time [20].



(a) (b)

Fig. 8. Z0 Compensation coil for HTS NMR magnet: (a) COMSOL electromagnetic analysis results, (b) photograph of the fabricated coil.

TABLE 3
OPTIMAL DESIGN RESULTS OF Z0 COMPENSATION COIL FOR THE 400 MHZ HTS NMR MAGNET.

Parameters	Compensation Coil
Inner Radius	24 [mm]
Outer Radius	24.9 [mm]
Axial Height	4.56 [cm]
Radial Thickness	0.9 [mm]
Operating Current (I_{op})	0.1 [A]
Number of Turns (R)	3 turns
Number of Turns (Z)	152 turns
Coil Length	69.6227 [m]
Magnetic Field @ I_{op}	10 [G]
Z0 ratio	93.14 [%]
Z2 ratio	6.77 [%]

Furthermore, given the potential differences between the magnetic field environment of the 400 MHz HTS NMR magnet and the introduced prototype coil, the proposed auto-tuning methods will be re-evaluated, and the tuning method demonstrating the best overshoot and settling time characteristics will be selected.

Additionally, to evaluate the fringe field applied to the 400 MHz HTS NMR magnet during the operation of the Z0 coil, the magnetic field was calculated at the region of the HTS magnet module coil closest to the Z0 coil. The magnetic field at the position (r = 51.8 mm, z = 0 mm) was 0.79 gauss at 0.1 A, which is sufficiently small to be considered negligible.

5. CONCLUSION

This paper presents a center field compensation system employing optimal control gains through auto-tuning to improve the temporal stability of HTS magnets.

Typically, when using PID control, the control gains are either chosen arbitrarily or calculated through complex and time-consuming methods. However, the auto-tuning technique enables faster and more accurate control. To verify the performance of the proposed field compensation system before its application to large scale HTS magnets, small scale background and compensation coils were designed and fabricated using copper coils.

Through experiments, the most suitable auto-tuning method for the system was identified and applied to the actual compensation coil control. It was confirmed that the central magnetic field remained stable at a constant value even under various conditions simulating HTS magnets: 1) field drift due to the screening current, 2) field fluctuation from the unstable power supply.

Following the validation in the proto-type field compensation system, a large scale Z0 compensation coil was designed and fabricated for the 400 MHz HTS NMR magnet available at KBSI. This Z0 compensation coil will be integrated with the high resolution magnetometer to be developed and the central field compensation system validated in this study. It is planned to be applied to the 400 MHz HTS NMR to improve the temporal stability of the NMR system. However, magnetic field distortions of various forms, beyond those induced by SCF-related drift or fluctuations, may also occur in the larger system. Additionally, further research is needed to determine whether the resolution of the actual NMR magnetometer can reach a controllable level. Therefore, it is essential to install this system in an actual 400 MHz HTS NMR system and implement various experiments to evaluate the field compensation system.

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