American Journal of Science and Technology
2015; 2(6): 304-310
Published online October 20, 2015 (http://www.aascit.org/journal/ajst)
ISSN: 2375-3846

American Association for Science and Technology

Keywords
Neculear Magnetic Resonance (NMR),
High Magnetic Field,
REBCO High-Temeprature Superconducting (HTS) Coil,
Quench,
Homogeneity of Magnetic Field

Received: September 24, 2015
Revised: October 7, 2015
Accepted: October 9, 2015

Electromagnetic-Induced Quench of an Inner-Shim Coil for a REBCO High-Temperature Superconducting NMR Magnet

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Citation
R. Piao, Y. Yanagisawa, J. Li, A. T. Saito, H. Nakagome, S. Iguchi, T. Takao, M. Hamada, S. Matsumoto, H. Suematsu. Electromagnetic-Induced Quench of an Inner-Shim Coil for a REBCO High-Temperature Superconducting NMR Magnet. *American Journal of Science and Technology*. Vol. 2, No. 6, 2015, pp. 304-310.

Abstract
A RE(rare earth)$Ba_2Cu_3O_x$ (REBCO) high-temperature superconducting (HTS) coil is a promising candidate to achieve a nuclear magnetic resonance (NMR) magnet operated at a magnetic field >23.5 Tesla (T), i.e. ^{1}H NMR frequency of 1 GHz. We developed and tested a 400 MHz (9.39 T) NMR magnet using an REBCO inner coil. The system included a low-temperature superconducting (LTS) shim coil inside the REBCO coil to compensate the large inhomogeneity of the magnetic field. After the magnet was successfully charged, and while the compensation of the magnetic field inhomogeneity was being carried out, the magnet was unexpectedly discharged due to a failure of the chiller used for the DC power supply. During the discharge, the magnetic flux was transferred from the main coil to the inner shim coil, and that coil quenched repeatedly due to the high induced current. After confirming that the coil was not damaged, the magnet was charged again and it was found that several components of the magnetic field inhomogeneity had increased compared to the previous operation. This phenomenon is explained as follows: the induced-current to the shim coil generated a large magnetic field and it added an undesired screening current in the REBCO coil, lead to the increase in the magnetic field inhomogeneity. The results suggest that a system to suppress the induced current is a requirement for a safe magnet operation and homogeneous magnetic field.

1. Introduction

Nuclear magnetic resonance (NMR) spectroscopy is widely used in fields of chemistry, physics, structural biology, and material science. As the sensitivity and the resolution of NMR spectrometers drastically increase with the magnetic field intensity, a higher magnetic field has been ever sought. However, conventional low-temperature superconducting (LTS) magnets which are widely used for NMR magnets cannot exceed 23.5 Tesla (T) (i.e. ^{1}H NMR frequency of 1 GHz) [1]. A super-high field NMR magnet with an operating frequency of >1 GHz is feasible if the design takes advantage of the high hoop stress tolerance of RE(rare earth)$Ba_2Cu_3O_x$ (REBCO) high-temperature superconducting (HTS) coils [1], in combination with LTS outer coils. In this light, we developed and tested the first LTS/REBCO NMR magnet operated at 400 MHz (9.39 T), as previously reported [2]. However, a screening current [3] induced in the wide surface of the superconducting layers in the REBCO coil interfered with the stable generation of a spatially homogeneous magnetic field, which is vital for NMR measurements. One major problem observed was that the screening current, induced during the magnet charging, shielded the magnetic field of a correction coil for the Z2 harmonic installed outside the main coils. Note that the main coils, i.e. the REBCO coil and the LTS coil, and the correction coil were connected in series and simultaneously charged with one DC power supply. As a result, a substantial Z2 field error harmonic [4] was observed [2], which was originally intended to be compensated by the correction coil. Based on the experience of the operation of the previous magnet, we developed a new magnet with a persistent mode shim coil installed inside the REBCO coil to effectively compensate the Z2 harmonic [5][6]. This shim coil is herein called the "inner-Z2 shim coil".

During the operation of this second magnet, the water-cooled chiller for the magnet's DC power supply shut down and the magnet was unexpectedly discharged in a dump mode. In the discharging process, the inner-Z2 shim coil was quenched repeatedly due to a high current generated by electromagnetic induction with the main coils. The magnet was charged again and we found that those quenches had affected the field homogeneity of the magnet. In the present work, these phenomena were investigated to clarify the risks of an inner shim coil for a super-high field NMR magnet.

2. Experimental

Figure 1 and Table 1 respectively show a cross section and the physical parameters of the LTS/REBCO NMR magnet with the inner-Z2 shim coil. Figure 2 shows a schematic of the electric circuit of the magnet. The REBCO inner coil, the LTS (Nb_3Sn and NbTi) outer coils, and the LTS (NbTi) correction coils were connected in series and continuously powered by a highly-stabilized DC power supply (Model 854, Danfysik) [2][7]. In a dump mode after power supply interruption, the stored energy is dissipated in the diode installed in the power supply (see figure 2).

The inner-Z2 shim coil was wound with an Nb_3Sn conductor and placed inside the REBCO coil as shown in figure 1. Therefore the coil showed a strong magnetic coupling effect with the main coils. The coil was operated in a persistent mode with a persistent current switch (PCS). The coil is self-protected with a high normal zone propagation velocity (NZPV).

All the coils were cooled in a liquid helium bath; the evaporated helium was re-condensed using a 4.2 K pulse-tube cryocooler (SRP-082B-F70H, Sumitomo Heavy Instruments, Ltd.) mounted on the top flange of the cryostat [2]. The power supply and the compressor for the cryocooler were cooled with water from a chiller.

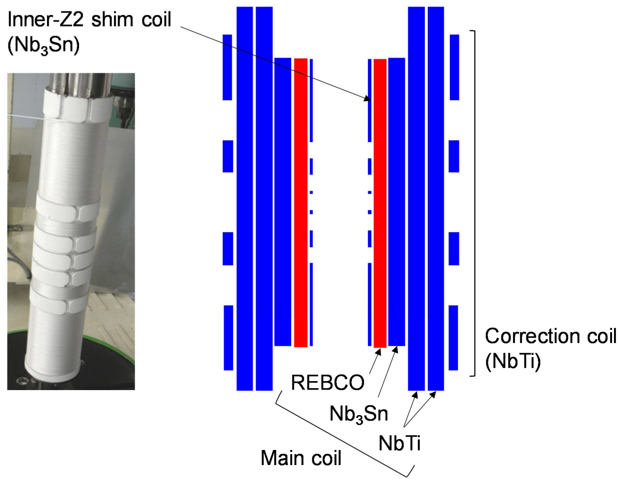

Figure 1. *The LTS/REBCO NMR magnet with the inner-Z2 shim coil operated at 400 MHz (9.39 T).*

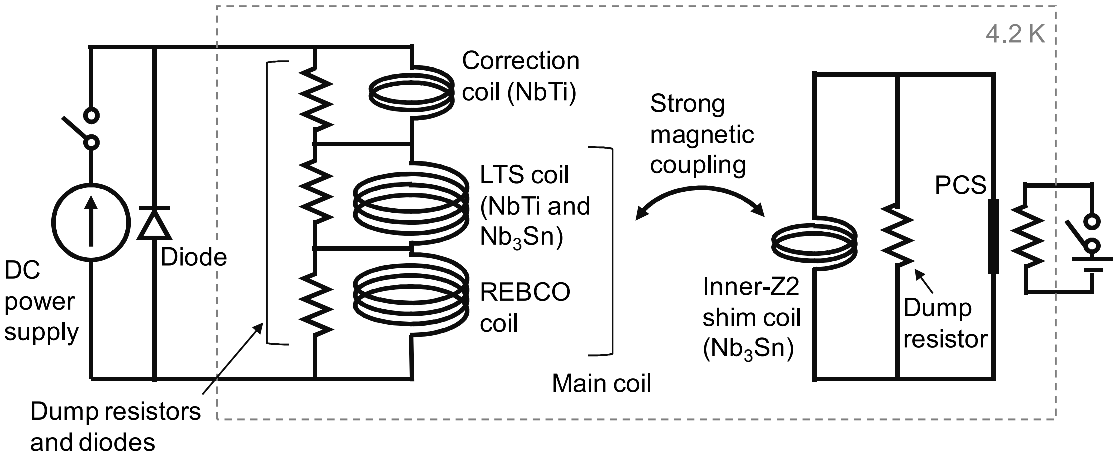

Figure 2. *Schematic of the electric circuit of the LTS/REBCO NMR magnet during a dump mode.*

Table 1. *Physical parameters of the 400 MHz (9.39 T) LTS/REBCO NMR magnet with the inner-Z2 shim coil.*

	Inner-Z2 shim coil (Nb_3Sn)	REBCO inner coil	Overall magnet except the inner-Z2 shim coil
Inner diameter (mm)	81.00	95.54	95.54
Outer diameter (mm)	87.84	125.19	331.75
Coil height (mm)	-	400	546
Number of layers	4	56	190
Total number of turns	1160	4392	40888
Length of the conductor (m)	308	1522	28927
Weight of the conductor (kg)	1.38	10.2	162
Operating current for 400 MHz (A)	-20 to 20	116	116
Inductance (H)	-0.32	3.28	75.4

3. Results and Discussion

3.1. The Induced-Quenches of the Inner-Z2 Shim Coil

After the flow of cooled water from the chiller was interrupted, the DC power supply and the pulse-tube cryocooler shut down. After this, the magnet's energy was dumped in a resistor inside the DC power supply. The left vertical axis of figure 3(a) shows the magnet current during the dump; $t = 0$. corresponds to the opening of the breaker in the DC power supply. As indicated by the open circles, the current decreased from the initial value of 116 A to 0 A in 35 minutes, a rate of −0.055 A/s. This rate is 5.5 times faster than the usual charging and discharging operation. The inductive voltage for the REBCO coil (V_{REBCO}) and that for the overall magnet (V_{all}) at $t = 0$ min. was -0.2 V and -5.1 V, respectively, as shown in figure 3(b).

During the discharge, inductive voltage spikes were observed in the REBCO coil (V_{REBCO}) as shown by (A'), (B'), (C'), and (D') in figure 3(b). These spikes indicate quenches of the inner-Z2 shim coil; i.e. due to electromagnetic induction from the main coils, the current of the inner-Z2 shim coil exceeded its critical current and quenched. The inner-Z2 shim coil was operated in persistent mode, so the current was increased until the quench. The radial magnetic field at the top end of the REBCO coil, B_r (denoted by the open triangles in figure 3(a)), also showed corresponding sudden drops labelled as (A), (B), (C) and (D) in the figure. The amplitude of the voltage spikes for V_{REBCO} increased with the quench repetition as shown in figure 3(b). This is because the decreasing magnetic field of the magnet increased the critical current of the inner-Z2 shim coil, thereby increasing the quench current and resulting in the larger inductive voltage.

After the shim coil quench at point (C) in figure 3(b), V_{REBCO} did not recover during the interval of $t = 12$ - 27 min. This indicates that the PCS for the inner-Z2 shim coil was also quenched following the coil quench, and it remained in a normal conducting state over this interval. During this time, the induced current was dissipated as Joule heating in the PCS and thus no quench occurred. As the PCS recovered to superconducting state at $t = 27$ min., the quench occurred again as shown at point (D') in figure 3(b). Considering the magnetic coupling between the inner-Z2 shim coil and the main coil and the time interval of 288 s (see figure 3(b)), the induced current in the shim coil at (D') in figure 3(b) is estimated to 248 A.

3.2. Effect of the Induced Quench on the Magnetic Field Homogeneity

After the magnet was discharged, the residual magnetic field [8] profile along the coil axis (i.e. z-axis) was measured with a Hall sensor (HGCA-3020, Lake Shore Cryotronics, Inc.). Accuracy of the measurement was about 0.1mT. as shown in figure 4. The field was generated by the screening current induced in the REBCO coil. Such a profile is generally observed for a LTS/HTS magnet [9][10] but the present profile at the center part is convex upward as shown by the inset in figure 4. Such a profile was not observed with a LTS/REBCO NMR magnet previously operated without an inner-Z2 shim coil, as shown by the open circles in figure 4. The Z2 error harmonic in this region was -11,435 Hz/cm^2 (-28.6 ppm of 400 MHz) as shown in the figure inset. This field profile can be explained as follows. During the dump, the high induced current in the inner-Z2 shim coil generated a magnetic field including a large Z2 harmonic, and this field induced the screening current in the REBCO coil; i.e., the field profile generated by the inner-Z2 shim coil was "copied" by the screening current.

The open circles in figure 5 show a field profile along the z-axis of the magnet center after the magnet was charged again to 400 MHz (9.39 T). The Z2 error harmonic was -19,807 Hz/cm^2. The error was ~10,000 Hz/cm^2 larger than the Z2 error of -9,389 Hz/cm^2 for the previous charging as shown by the closed triangles in figure 5. Considering that the Z2 harmonic of the residual field profile was -11,435 Hz/cm^2 (see again the inset of figure 4), this harmonic had been preserved during the re-charging process, resulting in the doubled Z2 error harmonic.

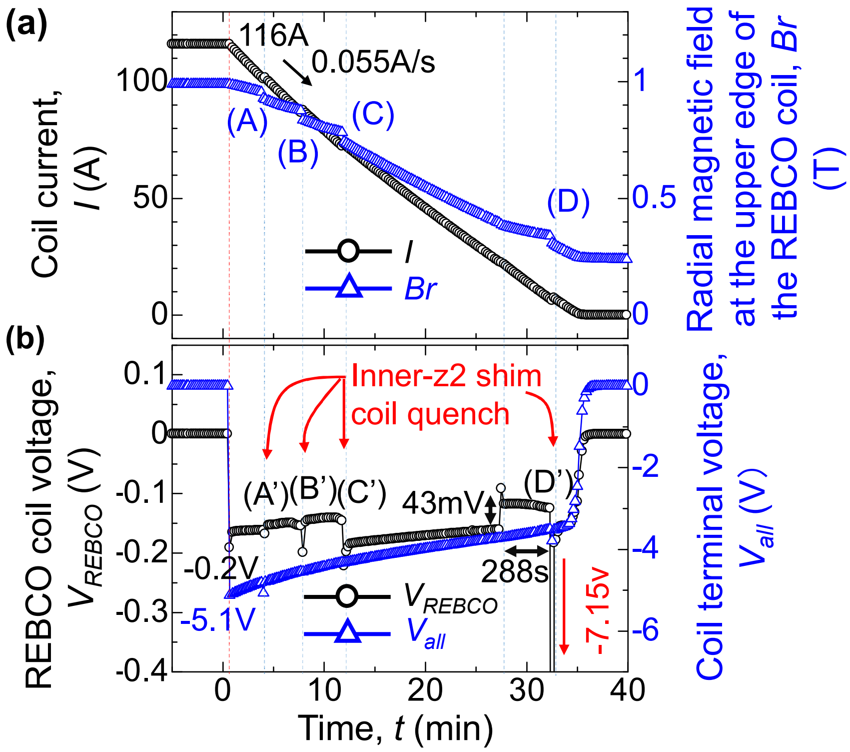

Figure 3. *(a) The coil current of the LTS/REBCO NMR magnet and the radial magnetic field at the upper end of the REBCO inner coil during the discharging. (b) The REBCO coil voltage (V_{REBCO}) and the overall voltage of the magnet (V_{all}) during the discharging process. The breaker of the DC power supply opened at t = 0 min.*

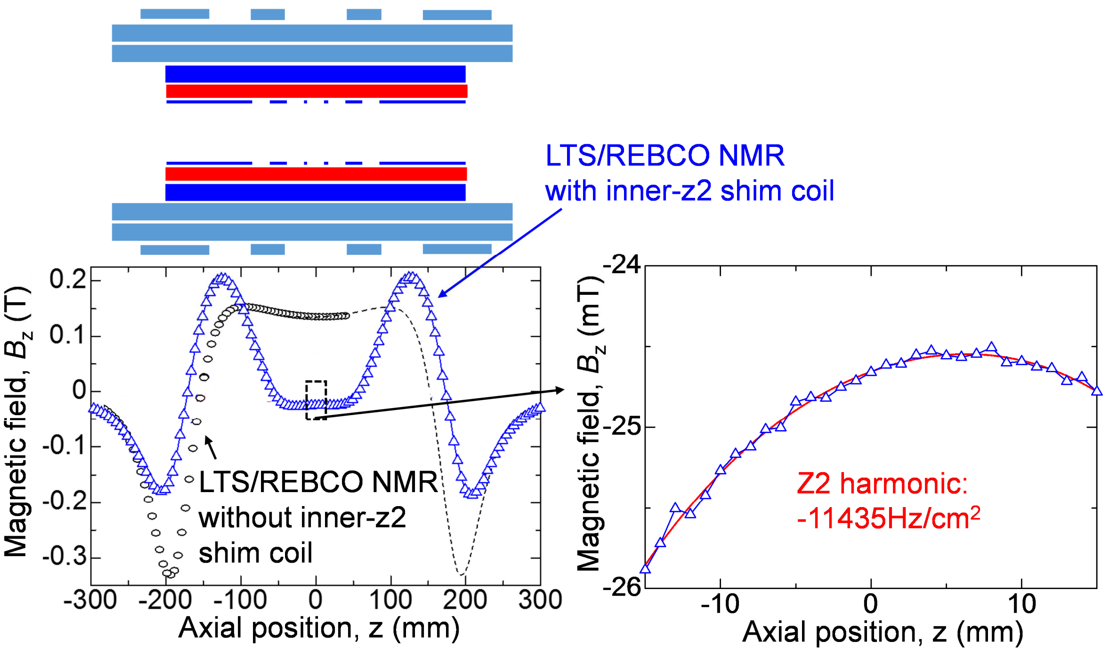

Figure 4. *Residual magnetic field profiles along the z-axis after the magnet discharge, which were measured with a Hall sensor. The fields were generated by the screening current in the REBCO coil. The open triangles (Δ) show the profile obtained after the unexpected discharge of the present LTS/REBCO NMR magnet operated at 400 MHz (9.39 T), accompanied by the induced-quenches of the inner-Z2 shim coil. The open circles (○) show the profile obtained after the controlled discharge of an LTS/REBCO NMR magnet without an inner-shim coil operated at <525 MHz (12.3 T) [2].*

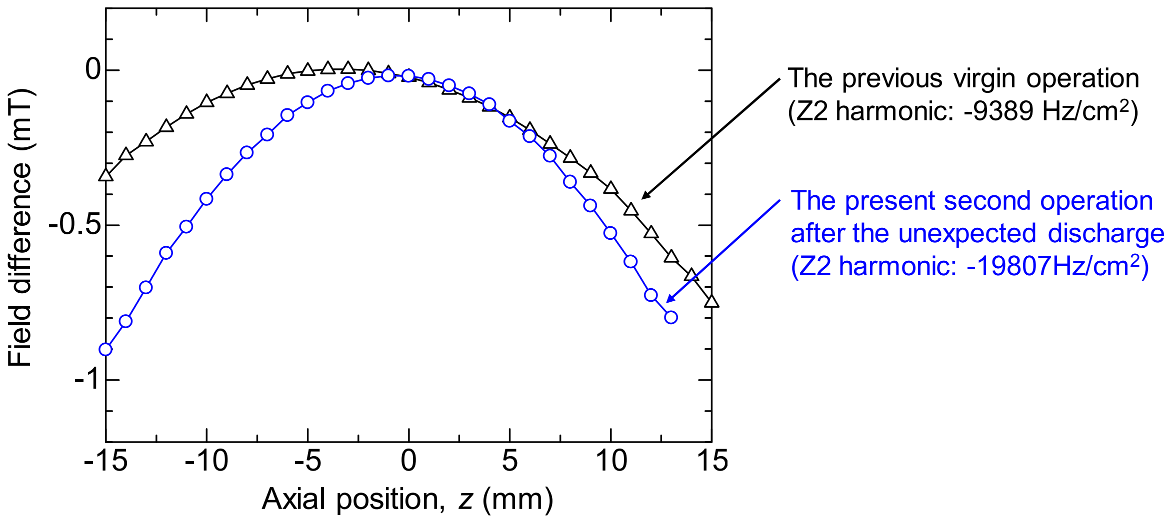

Figure 5. *Axial magnetic field profiles along the z-axis at the center of the LTS/REBCO NMR magnet operated at 400 MHz (9.39 T). The field was measured with a NMR Teslameter (PT2025, Metrolab Technology SA). The open circles (○) and the open triangles (△) respectively represent the profiles for the present second operation after the unexpected discharge and that for the previous virgin charging.*

This Z2 error harmonic was fully corrected with the inner-Z2 shim coil and the detailed field error harmonics were measured using a field mapping unit (FMU-1200, Resonance Research, Inc.). A small NMR sample was moved along a helical path with a radius of 8.5 mm, a height of 30 mm, and a rotation pitch of 2.5 mm. The axial magnetic field was measured at each point on the helical path. Measured field values within $z = \pm 15$ mm were expanded with spherical harmonics up to the 4th order [4]. Field homogeneity was evaluated for each harmonic including the zonal (axial) harmonics (Z1, Z2, Z3, …) and tesseral (radial) harmonics (X, Y, ZX, ZY, …) [4][11].

Figure 6 shows a measured field profile with the field mapping unit. Obviously, the amplitude of the field profile, i.e. field inhomogeneity, for the present second charging (the open circles) is larger than that for the previous charging (the closed triangles). Table 2 shows the field harmonics corresponding to the field profiles in figure 6. The amplitudes of the (X and Y) and (ZX and ZY) harmonics were~1.5 times larger than those of the previous charging. Thus, the additional screening current amplified not only the Z2 error harmonic, but also the tesseral error harmonics. This is explained as follows. Tesseral harmonics caused by the distortion of the REBCO coil shape [2] were amplified by the additional screening current induced by the magnetic field of the inner-Z2 shim coil.

3.3. Risks Produced by an Inner-Z2 Shim Coil

As shown in the present work, the inner-Z2 shim coil exhibited some problems during a dump mode (or a main coil quench) as the coil was strongly coupled with the main coils. In the present magnet, the inner-Z2 shim coil was fabricated with Nb_3Sn conductor, and therefore it was self-protected from the induced quench owing to the high normal zone propagation velocity (NZPV) [12]. However, for a super-high field NMR magnet operated at >1 GHz (23.5 T), an inner shim coil has to be fabricated with HTS materials, as Nb_3Sn coils cannot be used in such a high field. If such a HTS inner-shim coil undergoes an induced quench, it cannot be protected as the NZPV of a HTS is very low and the coil temperature would rise to a hazardous value [13].

In addition, the large current induced in the shim coil would worsen the field inhomogeneity by adding a screening current to the REBCO coil as shown in the present work, which is unfavorable for the field homogeneity correction.

Thus, the use of an inner-Z2 shim coil presents risks of damage to the coil itself and an increase in the field inhomogeneity. A system to automatically activate a heater in the PCS to prevent a high induced current and subsequent quench is therefore necessary in cases of unforeseen magnet dump or quench. In case of a main coil quench, a high current is induced within several seconds in both the shim coil and the REBCO coil. Rapid activation of the PCS for the shim coil and a sufficiently large dump resistor for the REBCO coil are required to suppress the peak current [13].

Table 2. *Field error harmonics for the magnetic field profiles presented in figure 5. These were measured after the correction of the Z2 error harmonic.*

Harmonics		Order, *n*	Amplitude (Hz/cm^n)	
			The previous virgin operation	The present second operation after the unexpected discharge
	Z	1	-12008	-14745
Zonal	Z2	2	-1246	167
(Axial)	Z3	3	731	-873
	Z4	4	-160	451
Tesseral	X	1	-4382	-283
(Radial)	Y	1	-5283	-10143

Harmonics		Order, *n*	Amplitude (Hz/cm^n)	
			The previous virgin operation	The present second operation after the unexpected discharge
	ZX	2	-3548	-5212
	ZY	2	-4164	-6687
	C2	2	-205	-663
	S2	2	2225	1199
	Z2X	3	-49	766
	Z2Y	3	-423	-77
	ZC2	3	196	542
	ZS2	3	87	327
	C3	3	115	118
	S3	3	121	248

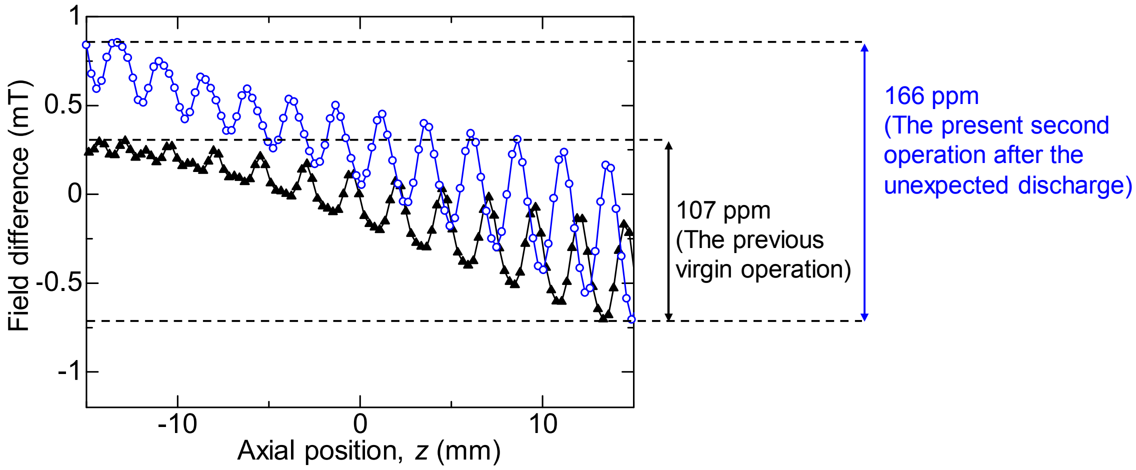

Figure 6. *Axial magnetic field profiles along a spiral path in the center of the LTS/REBCO NMR magnet operated at 400 MHz (9.39 T), as measured with a field mapping unit. The open circles (○) and the closed triangles (▲) respectively represent the profile for the present second operation after the unexpected discharge and that for the previous virgin operation.*

4. Conclusions

In this study, an unexpected discharge of a 400 MHz (9.39 T) LTS/REBCO NMR magnet with a persistent mode inner shim coil was investigated. The study found that:

1) During the discharge, electromagnetic-induced quenches occurred in the inner shim coil. Such a quench will cause damage on the coil if the shim coil is wound with HTS.
2) Those quenches decrease field homogeneity of the magnet by inducing an additional screening current in the REBCO coil.
3) A large inner shim coil presents these risks, which should be considered in the design of a LTS/REBCO NMR magnet.

Acknowledgement

This study was carried out by the Japan Science and Technology Agency (JST) under the Strategic Promotion of Innovative Research and Development Program.

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