**Operation of a 400 MHz NMR magnet using a (RE:Rare
Earth)Ba₂Cu₃O_{7-x} high-temperature superconducting coil:
Towards an ultra-compact super-high field NMR spectrometer
operated beyond 1 GHz**

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1 **Abstract**

2 High-temperature superconductors (HTS) are the key technology to achieve super-high
3 magnetic field nuclear magnetic resonance (NMR) spectrometers with an operating
4 frequency far beyond 1 GHz (23.5 T). (RE)Ba₂Cu₃O_{7-x} (REBCO, RE: rare earth)
5 conductors have an advantage over Bi₂Sr₂Ca₂Cu₃O_{10-x} (Bi-2223) and Bi₂Sr₂CaCu₂O_{8-x}
6 (Bi-2212) conductors in that they have very high tensile strengths and tolerate strong
7 electromagnetic hoop stress, thereby having the potential to act as an ultra-compact
8 super-high field NMR magnet. As a first step, we developed the world's first NMR
9 magnet comprising an inner REBCO coil and outer low-temperature superconducting
10 (LTS) coils. The magnet was successfully charged without degradation and mainly
11 operated at 400 MHz (9.39 T). Technical problems for the NMR magnet due to
12 screening current in the REBCO coil were clarified and solved as follows: (i) a
13 remarkable temporal drift of the central magnetic field was suppressed by a current
14 sweep reversal method utilizing ~10 % of the peak current. (ii) a Z₂ field error
15 harmonic of the main coil cannot be compensated by an outer correction coil and
16 therefore an additional ferromagnetic shim was used. (iii) large tesseral harmonics
17 emerged that could not be corrected by cryoshim coils. Due to those harmonics, the
18 resolution and sensitivity of NMR spectra are ten-fold lower than those for a
19 conventional LTS NMR magnet. As a result, a HSQC spectrum could be achieved for a
20 protein sample, while a NOESY spectrum could not be obtained. An ultra-compact 1.2
21 GHz NMR magnet could be realized if we effectively take advantage of REBCO
22 conductors, although this will require further research to suppress the effect of the
23 screening current.

24

1 **Keywords:**

2 Ultra-compact super-high field NMR magnet beyond 1 GHz

3 REBCO high temperature superconducting coil

4 Screening current

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I. Introduction

NMR spectrometers that operate at a frequency beyond 1 GHz are required for further breakthroughs in structural biology and materials sciences. Conventional NMR magnets cannot exceed 1 GHz (corresponding to a magnetic field of 23.5 T) as the critical current density of low temperature superconductors (LTS) decreases steeply above 23 T. The use of magnets made from high temperature superconductors (HTS) such as (i) $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10-x}$ (Bi-2223) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8-x}$ (Bi-2212), and (ii) $(\text{RE})\text{Ba}_2\text{Cu}_3\text{O}_{7-x}$ (REBCO, RE: rare earth materials such as Y and Gd), provides a sufficient high current density above 1 GHz,¹ enabling an NMR magnet to exceed that frequency. In fact, a magnetic field strength of 34 T, equivalent to a ^1H NMR frequency of 1.45 GHz, was achieved using a Bi-2212 inner coil,² while 35.4 T (1.5 GHz) can be attained with a REBCO inner coil in a background field of 31 T,³ Thus, a 1.5 GHz (35.4 T) NMR magnet is in principle made possible if we employ low-field LTS outer coils and high-field HTS inner coils, or a “LTS/HTS NMR magnet”.^{4,5}

When superconducting magnets are charged they generate enormous hoop stresses on the conductors which are proportional to the current density. Therefore the current density of a high-field HTS coil is limited by the conductor hoop strength.^{6,7} A higher coil current density, such as 300 A/mm², is made possible by using REBCO conductors that can tolerate >700 MPa,⁸ while a lower coil current density such as 100 A/mm² is available using conventional Bi-2223 conductors that can tolerate ~200 MPa.⁹ To achieve a higher NMR magnetic field with a smaller magnet, a REBCO inner coil is preferred over a Bi-2223 inner coil.

We started a project to develop a beyond 1 GHz NMR spectrometer using a LTS/Bi-2223 NMR magnet in 2007;¹⁰ note that Bi-2223 was the only commercialized HTS candidate available at that time. In the first stage of development, a 500 MHz LTS/Bi-2223 NMR spectrometer operated in external current mode (i.e. driven mode) was developed and installed in RIKEN.^{11,12} The magnetic field for the LTS/Bi-2223

1 magnet is affected by the screening current which is induced by the radial component of
2 the local magnetic field on the Bi-2223 multi-filamentary tape conductor.¹³ Positive
3 drift in the magnetic field intensity with time was observed due to relaxation of a
4 screening current due to flux creep.¹⁴ The drift can be suppressed by using a “current
5 sweep reversal method”.¹⁵ A field fluctuation due to a DC current supply was stabilized
6 using a modified ²H field-frequency internal lock system.^{11,16} The spatial magnetic field
7 inhomogeneity was effectively corrected by conventional cryoshim coils and room-
8 temperature shim coils. The qualities of the multi-dimensional NMR spectra such as
9 HSQC, HNCACB and NOESY obtained for an aqueous protein solution sample were
10 nearly equivalent to those obtained by a conventional 500 MHz NMR.¹¹ The second
11 stage of the development, with the goal of developing a 1.03 GHz LTS/Bi-2223 NMR
12 spectrometer, is intended to be completed in FY2014. It will become the world’s first
13 high field solution NMR spectrometer operated beyond 1 GHz.

14 As noted above, the current density for a Bi-2223 coil is not particularly high and
15 therefore the NMR magnet becomes very large as the magnetic field increases more and
16 more; e.g. the total weight of superconductors required for a 1.3 GHz LTS/Bi-2223
17 NMR magnet design⁷ is 10-fold larger than that for a 1.03 GHz LTS/Bi-2223 NMR
18 magnet. To achieve a higher NMR magnetic field with a smaller magnet, a REBCO
19 inner coil is preferred over a Bi-2223 inner coil. Thus, we started a further project to
20 develop an LTS/REBCO NMR spectrometer.¹⁷ As a first step, we built the world’s first
21 400-500 MHz LTS/REBCO NMR spectrometer in order to clarify major technical
22 challenges in developing a small super-high field NMR, the results of which are
23 described in this paper.

24 REBCO coils are known to exhibit many technical problems¹⁸ such as (i)
25 significant effect of the screening current induced magnetic field on the field stability
26 and field homogeneity,^{19,20} (ii) delamination of the multi-layered REBCO conductors²¹
27 resulting in degradation in the coil performance, due to thermal stress caused by epoxy

1 impregnation,^{22,23} and (iii) conductor overheating and permanent damage due to thermal
2 runaway of the coil, i.e. coil quenching.^{24,25,26} During the past several years, the basic
3 mechanism for these problems has been investigated and effective partial remedies
4 proposed.¹⁸ However, REBCO coils are still at an early stage of development and very
5 few REBCO magnet systems have been built.²⁷ Therefore, preliminary research has
6 been conducted in our laboratory prior to magnet development and published elsewhere.
7 This work is only briefly described in the present paper.

8 The topics investigated regarding the LTS/REBCO NMR magnet in this paper are
9 as follows.

10 (a) Effects of the screening current-induced magnetic field on the homogeneity and
11 stability of the magnetic field.

12 (b) Effective remedies for a magnetic field drift for the LTS/REBCO NMR magnet.

13 (c) Magnetic shielding effect by the REBCO coil winding against correction coils and
14 cryoshim coils; i.e. REBCO superconducting layers reduce the performance of the
15 correction coils and the cryoshim coils installed outside the magnet.

16 (d) Quality of the NMR spectra. The results are closely compared to those for the
17 previous LTS/Bi-2223 NMR magnet.¹¹

18 Furthermore, perspectives for a paradigm shift in the field of super-high field NMR
19 spectrometers will be discussed.

21 **II. Experimental**

22 **A. REBCO inner coil**

23 REBCO conductors made by Fujikura Ltd. were used for the high-field inner coil of
24 the NMR magnet. The REBCO conductors are multi-layered type of superconductors,
25 comprising a 75 μm -thick Hastelloy substrate, a ~ 1 μm -thick buffer layer, a ~ 2 μm -thick
26 GdBCO superconducting layer, and a 75 μm -thick copper stabilizer. The conductor is 5
27 mm in width and 0.15 mm in thickness, insulated with double-wrapped polyimide

1 insulation tape. The insulated conductor is 0.25 mm in thickness. The REBCO inner
2 coil was fabricated by JASTEC Inc.. The coil is 81.3 mm in inner diameter, 118.7 mm
3 in outer diameter and 400 mm in length. A layer winding method, i.e. a solenoid
4 winding, was employed to better obtain magnetic field homogeneity.¹² Six pieces of
5 REBCO conductors were used for the coil and there are five soldered joints between
6 conductors in the winding. The joints are located at the both ends of the coil. During
7 winding, we controlled the winding diameter to avoid a distortion of the coil winding
8 shape; a Mylar sheet was placed over each winding layer having a joint for flattening
9 the surface of the layer. After winding the coil, it was reinforced by an outer binding
10 made from brass wire. The coil is shown on the bottom-left corner of FIG. 1.

11 Based on our previous investigation,²² epoxy impregnated REBCO coils are
12 degraded due to excessive transverse tensile stress appearing during cool down. The
13 stress is due to the mechanically hard nature of epoxy at low temperatures and the easily
14 delaminated multi-layered structure of the REBCO conductor.^{21,23} The degradation can
15 be suppressed if the REBCO coil is impregnated with soft polymers such as paraffin
16 wax, as the transverse tensile thermal stress is then diminished. Thus, we impregnated
17 the REBCO inner coil with paraffin wax.

18

19 **B. LTS/REBCO NMR magnet**

20 The NMR magnet comprises the REBCO inner coil, Nb₃Sn coils, NbTi coils and
21 NbTi correction coils. The outer LTS coils are a part of a conventional 600 MHz (14.1
22 T) NMR magnet produced by JASTEC Inc., as seen in FIG. 1. The innermost Nb₃Sn
23 coil was replaced by the REBCO coil to achieve a LTS/REBCO NMR magnet.
24 Although the magnet can be operated at 600 MHz (14.1 T), it was mainly operated at
25 400 MHz (9.39 T). In the case of 400 MHz operation, the REBCO coil generates 1.86
26 T, while the LTS coil 7.53 T, at an operating current of 109.4 A. The physical
27 parameters for the inner REBCO coil and the LTS/ REBCO NMR magnet are listed in

TABLE I. As the available REBCO conductor size is limited (5 mm in width and 0.15 mm in thickness), and the coil current is limited by the operating current of the LTS coils, the overall current density of the REBCO inner coil is as low as 80.9 A/mm² for 400 MHz. Therefore, the present magnet cannot be made ultra-compact in size.

All superconducting coils are connected in series and charged simultaneously by a highly-stabilized DC current supply, with a current fluctuation amplitude <1 ppm, developed by Danfysik (model 854).¹¹ Each coil is shunted by a cold dump resistor and a cold diode for quench protection.²⁶

The LTS/REBCO coil was cooled by liquid helium at 4.2 K. A 4 Kelvin two-stage pulse-tube cryocooler (SRP-082B-F70H, Sumitomo Heavy Instruments, Ltd.) having a cooling power of 1 W was installed on the top flange of the cryostat to re-liquefy vaporized helium gas.¹¹ The first stage of the cryocooler (40 W at 45 K) cools current leads made from bulk HTS- that connect the superconducting coils at 4.2 K and the external devices at room temperature; the HTS current lead has a low thermal conductivity, while it has a high electrical conductivity. Therefore, refilling of liquid helium is basically unnecessary for the LTS/REBCO NMR magnet.

A commercial 600 MHz triple resonance probe (Bruker Biospin) was modified to be a 400 MHz triple resonance probe. A DRX NMR console made by Bruker Biospin was used for NMR measurements.

III. Experimental results

A. Hysteresis effect of the central magnetic field intensity

The LTS/REBCO NMR magnet was successfully charged to 144.6 A, corresponding to a magnetic field intensity of 12.32 T, i.e. 524.7 MHz. As expected, the REBCO innermost coil did not show any degradation in performance.

A screening current-induced magnetic field, B_s , is an additional magnetic field produced by the screening current induced by the magnetic field perpendicular to the

1 broad surface of the REBCO conductors. The field is estimated by subtracting the
2 expected magnetic field intensity from the actual magnetic field intensity.

3 It is known that the screening current induced magnetic field intensity for an HTS
4 coil shows a hysteresis effect.¹⁴ As the coil current increases, a pair of oppositely
5 directed screening currents is induced from the upper edge and lower edges of the tape
6 conductor which screens the region inside the superconductor. The magnetic field
7 penetration depth²⁸ increases with the coil current and finally it fully penetrates over the
8 conductor width. When the coil current is decreased, the opposite screening current is
9 induced on both edges of the conductor. They result in a hysteresis effect of the
10 magnetic field intensity. The effect resembles the hysteresis loop for the magnetization
11 of a type II superconductor.¹⁴

12 The hysteresis effect for the LTS/REBCO coil was measured while the coil current
13 was increased to 144.6 A, i.e. 12.32 T and 524.7 MHz, and decreased to 0 A. The B_s vs.
14 current characteristic is shown in FIG. 2(a). The intensity of B_s initially increased with
15 the coil current as shown by the curve-1, which then saturated to -120 mT at 60 A due
16 to full penetration of the screening current. After saturation, the intensity of B_s slightly
17 decreases with coil current as shown by the curve-2, due to the decrease in the critical
18 current density with the magnetic field intensity. For 144.6 A, B_s is -100 mT,
19 corresponding to -0.81 % of the central magnetic field intensity of 12.32 T. If the coil
20 current is kept constant at 144.6 A, the negative B_s decays with time due to relaxation of
21 the screening current, resulting in an increase in the actual magnetic field intensity. This
22 phenomenon will be described later.

23 With a decrease in the coil current, B_s deviates to the curve-3 from the curve-2 as
24 shown in FIG. 2(a), and the remnant screening magnetic field is as large as 140 mT.
25 Several notches can be seen on curve-2 and curve-3 showing the magnetic field drifts
26 with time during the current holds, which are caused by the relaxation of the screening
27 current.²⁹

1 After charging/discharging the LTS/REBCO NMR magnet, the REBCO inner coils
2 was independently charged and discharged in both polarities; the B_s hysteresis effect is
3 shown by the blue dashed line in FIG. 2(a). The hysteresis loop does not show
4 saturation as the critical current densities in the REBCO inner coil is higher than that
5 under the high magnetic field generated by the LTS outer coils.

6 FIGURE 2(b) shows the B_s hysteresis for the LTS/Bi-2223 NMR magnet which is
7 described in the previous paper.¹¹ The Bi-2223 inner coil is 81.2 mm in inner diameter,
8 121 mm in outer diameter and 375 mm in length; i.e. its configuration is similar to the
9 REBCO inner coil. The B_s vs. current curve during a current ramp from ~75 A to 145.0
10 A is plotted by the black solid line; note that 145.0 A corresponds to 504.4 MHz, 11.85
11 T for the LTS/Bi-2223 NMR. Here, B_s is already saturated at ~75 A. The B_s for 145.0 A
12 is -12 mT, 0.10% of the central magnetic field. Thus, the B_s for the LTS/REBCO NMR
13 magnet is 8.5-fold larger than that for the LTS/Bi-2223 NMR magnet. The blue dashed
14 line in FIG. 2(b) shows a B_s hysteresis loop for the Bi-2223 inner coil. The loop shows
15 saturation, due to lower full penetration field of the multi-filamentary Bi-2223
16 conductors. Thus, it is clear that the effect of the screening current on the magnetic field
17 intensity for the LTS/REBCO NMR magnet is enormous compared to the LTS/Bi-2223
18 NMR magnet.

19 The difference is interpreted as follows: for a REBCO tape conductor, the screening
20 current is freely induced over a superconducting flat surface,¹⁸ resulting in an enormous
21 screening current-induced magnetic field intensity. On the other hand, Bi-2223
22 conductors comprise multi-filaments embedded in a silver matrix. The screening current
23 is induced between partly bridged multi-filaments,^{13,30} and therefore it is limited by
24 superconducting bridges incidentally formed between filaments. Thus, the screening
25 current induced magnetic field intensity for the LTS/REBCO NMR magnet is larger
26 than that for the LTS/Bi-2223 NMR magnet.

B. Magnetic field drift with time due to relaxation of the screening current

After the magnet was charged to 138.6 A, i.e. 11.81 T and 503.0 MHz, the temporal drift of the actual magnetic field intensity was measured using an NMR Teslameter (PT2025, Metrolab Technology SA). As shown by the solid-black line in FIG. 3(a), a remarkable positive drift of the actual magnetic field intensity at 525 MHz occurs, due to relaxation of the negative B_s with time. The magnetic field drift rate at $t = 1$ h is as large as 137 ppm/h, 10-fold larger than that for the LTS/Bi-2223 NMR magnet, 19 ppm/h at $t = 0$ h.¹¹ The magnetic field drift rate had decreased to 1.51 ppm/h at $t = 100$ h, which is still two orders of magnitude larger than that <0.01 ppm/h (10^{-8} /h) shown for LTS NMR magnets. For the LTS/Bi-2223 NMR magnet,¹¹ the drift rate at $t = 110$ h was 0.05 ppm/h (5×10^{-8} /h) as shown by the black solid line shown in FIG. 3(b). The curve of the magnetic field drift with time can be fitted by a logarithm function and a long term temporal change can be predicted. Based on the drift for the LTS/REBCO NMR magnet, the time duration to reach 0.01 ppm/h is estimated to be ~ 600 days (~ 1.6 years), impractically long for a NMR spectrometer.

A current sweep reversal method¹⁵ was used to stabilize the temporal magnetic field drift. The magnetic field drift is due to creep of the fluxoid, i.e. relaxation of the screening current,¹⁴ in the HTS tape conductor and the current sweep reversal forms a barrier for flux entrance at the upper and lower edges of the conductor, preventing flux creep advancement. Thus, a current sweep reversal by 5% was applied as shown by the blue dashed line seen in FIG. 3(a); it dramatically reduced the drift rate in the magnetic field intensity to 0.12 ppm/h at $t = 100$ h, two orders of magnitude smaller than that without applying the current sweep reversal method. The field drift rate was estimated to reach 0.01 ppm/h (10^{-8} /h) in 60 days. The red dashed-dotted line in FIG. 4(a) shows the drift after discharging to 470 MHz from 525 MHz, i.e. 12% reversal. The drift was fully suppressed. The required reverse current for the LTS/REBCO NMR magnet was several- to ten-fold larger than that for the LTS/Bi-2223 NMR magnet, i.e. 1% as shown

1 in FIG. 3(b).¹¹ It is a disadvantage of the LTS/REBCO NMR magnet, as the magnet
2 needs to be charged to a higher current than the operating current.

4 **C. Magnetic field inhomogeneity due to shielding effect of the screening current**

5 After the measurements of the magnetic field drift, the central magnetic field
6 distribution along the z -axis, i.e. the coil axis, was measured at ~ 500 MHz using the
7 NMR Teslameter. As shown by FIG. 4(a), a notable inhomogeneity of magnetic field
8 distribution was observed for the LTS/REBCO NMR magnet. This convex distribution
9 is due to the Z2 harmonic.^{31,32} The harmonic is 41.5 kHz (i.e. -83 ppm of 500 MHz) at
10 ± 1 cm, which is 18-fold larger than the designed correction ability of the Z2 cryoshim
11 coil of ~ 2.8 kHz (i.e. ~ 5.6 ppm of 500 MHz). This is a unique phenomenon of the
12 LTS/REBCO NMR magnet and was not observed for the LTS/Bi-2223 NMR magnet,
13 as shown in FIG. 4(b).¹¹

14 The magnetic field generated by the main coils of a NMR magnet includes both Z2
15 and Z4 harmonics, which are compensated by the outside correction coil.³³ The
16 magnetic field of the main coils include a Z2 harmonic of -151.25 kHz (i.e. -302.5 ppm
17 of 500 MHz) at $z = \pm 1$ cm, In the case of the LTS/Bi-2223 NMR magnet, the
18 compensation worked very well and the harmonic was fully compensated as described
19 above. However, for the LTS/REBCO NMR magnet, 27.4% of this Z2 harmonic, -41.5
20 kHz (i.e. -83 ppm of 500 MHz) at $z = \pm 1$ cm, is uncompensated by the outside
21 correction coil due to the shielding effect by the screening current induced in the
22 REBCO coil.

23 The magnet was discharged to 400 MHz, i.e. 9.39 T, to make NMR measurements.
24 The magnetic field distribution along the z -axis was measured using the NMR
25 Teslameter. The distribution of the magnetic field intensity, $B_z(z)$, over $z = \pm 1$ cm is
26 represented by the red open circles in FIG. 5. The vertical axis shows the normalized
27 magnetic field intensity given as

$$(B_z(z) - B_z(z=0)) / B_z(z=0) \quad \text{Eq. (1).}$$

The Z2 harmonic at $z = \pm 1$ cm is -66 ppm of 400 MHz (i.e. -26.4 kHz). As the Z2 cryoshim coil cannot correct such a large harmonic, passive shimming³¹ was adopted by placing 0.2 mm diameter ferromagnetic wires outside a room temperature shim unit, which corrected the Z2 harmonic. The Z2 harmonic over ± 1 cm was finally reduced to -0.15 ppm (i.e. 60 Hz) through a trial-and-error process as shown by the blue closed triangles in FIG. 5. The magnetic field was further corrected by cryoshim coils. Currents for the cryoshim coils such as Z1, Z2, X, Y, ZX, ZY, C2 and S2 were converged using field mapping measurements obtained from a field mapping system (FMU-1200, Resonance Research, Inc.). We made ~50 iterations of a cryoshim coil current operation and a field-mapping measurement. The hysteresis effect of the field error harmonics due to the screening current made the field-correction process difficult. In addition, the field harmonics generated by the cryoshim coils were noticeable shielded by the screening current induced in the REBCO inner coil and therefore the field correction efficiency was lower than expected. As a result, several tesseral harmonics^{31,32} cannot be corrected. The details will be described in the following section.

D. Field stabilization by ²H field-frequency lock operation

The magnetic field fluctuation of the LTS/REBCO NMR magnet operated in the external current mode¹¹ comprises three components:

- a) Long-term field drift due to relaxation of the screening current-induced magnetic field in the REBCO coil.
- b) Daily variations in the magnetic field with a peak-peak amplitude of 0.4 ppm. They were due to daily changes in the environmental temperatures of the DC power supply.

1 c) Short-term field ripples with a peak-peak amplitude the <0.2 ppm; these
2 fluctuations were due to short-term current ripples caused by the DC power supply.

3 These fluctuations can be continuously stabilized to <1 ppb (10^{-9}), by using an ^2H
4 field-frequency lock, as described in a previous paper.¹¹ Thus, the field homogeneity
5 was improved based on the lock level by using room-temperature shim coils.

6 7 **E. Quality of NMR spectra**

8 The magnetic field inhomogeneity was further corrected with RT shim coils by
9 observing the ^1H spectrum line shape for 1% CHCl_3 in acetone- d_6 . FIGURE 6(a) shows
10 the ^1H spectrum line shape obtained for the sample. The spectrum was obtained by a
11 single scan. The half-height line width, with a sample spin of 20 Hz, is 0.3 Hz, while
12 those for 0.55% and 0.11 % of the main peak are 10 Hz and 40 Hz, respectively, which
13 are several-fold broader than those for a conventional LTS NMR. Therefore, higher
14 order zonal harmonics^{31,32} such as Z3, Z4 and Z5 seem to remain in the spectrum as the
15 base width of the spectrum is broad.³⁴ Large spinning sidebands at ± 20 Hz and ± 40 Hz
16 are due to uncorrected tesseral harmonics such as X, Y, ZX, ZY, C2, and S2.

17 Due to the uncorrected tesseral harmonics, the ^1H spectrum line shape without
18 sample spin was 10-fold broader than that for a conventional NMR, as seen in FIG.
19 6(b); the half height line width is 15 Hz, while those for 0.55% and 0.11% of the main
20 peak are 235 Hz and 286 Hz, respectively. Thus, it became clear that the spectrum
21 resolution for the LTS/REBCO NMR spectrometer is >10 Hz (0.25 ppm) without
22 sample spin, which is insufficient for high-resolution NMR measurements, while it
23 becomes better with sample spin. Therefore, it is difficult to suppress a large water
24 signal and achieve a NOESY spectrum required for protein structural determination.

25 FIGURE 7 shows the ^1H sensitivity for 0.1% ethylbenzene in CDCl_3 . The spectrum
26 was obtained by a single scan with a sample spin of 20 Hz. The sensitivity is determined
27 by the ratio of the central peak of the quartet at 2.7 ppm to the noise over 0.4 ppm, and

1 is 28.2. The NMR sensitivity is $< 10\%$ of the conventional 400 MHz LTS NMR due to
2 spectrum broadening.

3 Though the resolution and sensitivity for the LTS/REBCO NMR is about 10-fold
4 lower than those achieved with conventional LTS NMR magnets, some types of multi-
5 dimensional NMR spectra are achievable on protein samples using the LTS/REBCO
6 NMR. FIGURE 8 illustrates such an example, that of a 2D-HSQC spectrum for ^{13}C - and
7 ^{15}N -labeled chlorella ubiquitin. FIGURE 8(a) shows a HSQC spectrum obtained by the
8 LTS/REBCO NMR magnet operated at 400 MHz, while FIG. 8(b) shows that by a
9 conventional 500 MHz LTS NMR magnet. The measurement was made without sample
10 rotation. Although several peaks disappeared in FIG. 8(a) compared with FIG. 8(b), as
11 indicated by the dashed circle in FIG. 8(b), they reappeared if we lowered the 2D-
12 contour threshold level. If there is magnetic field instability with time, noticeable t_1
13 noise will appear along the t_1 axis.³⁴ As we have no t_1 noise visible in FIG. 8(a), the
14 temporal magnetic field stability is sufficient. As the quality of the line shape for the
15 LTS/REBCO NMR is low, water suppression for the NMR spectrum is not sufficient;
16 therefore ^1H peaks near the water signal, such as alpha protons, are usually invisible.
17 The HSQC spectrum shown-in FIG. 8(a) is not affected by poor water suppression.

18 Our work to this point has shown that it is impossible to use the LTS/REBCO NMR
19 to measure the NOESY spectra indispensable for structure determination of proteins, as
20 it requires a better spectrum line shape than that achievable thus far. Thus, more
21 improvements in magnetic field homogeneity must be made, if we are to apply the
22 LTS/REBCO NMR spectrometer to a wide variety of multi-dimensional high-resolution
23 NMR measurements.

25 **IV. Discussion**

26 **A. Origins of the field inhomogeneity**

1 The results reported above demonstrate that the NMR spectra obtained by the
2 LTS/REBCO NMR magnet are about 10-fold broader than those obtained by the LTS
3 NMR magnet, due to remnant magnetic field inhomogeneity, due especially to the
4 residual tesseral harmonics. Their origins are investigated in the following paragraphs
5 based on the field mapping.

6 TABLE II shows error field harmonics of the LTS/REBCO NMR magnet operated
7 at 400 MHz, measured by a field mapping unit (FMU-1200, Resonance Research, Inc.)
8 before and after the field correction using cryoshim coils; note that the Z2 ferromagnetic
9 shim has been applied. The cryoshim coil current is also shown in the table. For
10 comparison, corresponding values obtained for the LTS/Bi-2223 NMR magnet operated
11 at 500 MHz¹¹ are shown in TABLE III. TABLE IV shows the expected design shim
12 performance (the second column) for a maximum available current of 20 A. The ratio
13 between the real shim performance and the expected design shim performance for the
14 LTS/REBCO NMR magnet, i.e. the efficiency in the cryoshim coil performance, is also
15 shown in the third column of the table. For comparison, the efficiency in the LTS/Bi-
16 2223 NMR magnet operated at 500 MHz¹¹ is shown in the fourth column.

17 For the LTS/REBCO NMR magnet data shown in TABLE II, tesseral harmonics of
18 ZY, C2, and S2 are notably larger than those for the LTS/Bi-2223 NMR magnet shown
19 in TABLE III, by factors of 2.4, 15.0, and 1.5 respectively; note that the large Y
20 component for the LTS/Bi-2223 NMR magnet is due to the fringe field of an adjacent
21 500 MHz NMR magnet. It is probable that the larger amount of tesseral harmonics for
22 the LTS/REBCO NMR magnet is due to a slight non-axisymmetric shape of the
23 REBCO coil winding, owing to the extremely thin and flexible REBCO conductors
24 and solder joints in the winding; the error harmonics might be amplified by the effect of
25 screening currents and magnetization of the Hastelloy substrate.

26 According to TABLE IV, the performance of the radial cryoshim coils for the
27 LTS/REBCO NMR magnet is notably degraded due to the shielding effect of the

1 screening current induced in the REBCO inner coil. The performance in compensation
2 of X, Y, ZX, ZY, C2 and S2 are respectively degraded to 4.1%, 2.2%, 0.6%, 0.3%,
3 3.6% and 4.6% of the theoretical design. Therefore, large residual tesseral harmonics for
4 the LTS/REBCO NMR magnet, such as ZY, C2 and S2, seen in TABLE II, cannot be
5 effectively corrected by the cryoshim coils. On the other hand, in the case of the
6 LTS/Bi-2223 NMR magnet, the performance of the X, Y, ZX and ZY cryoshim coils
7 are only reduced to 15%, 35%, 25% and 25%, respectively, of the theoretical design
8 values, which are 10-fold better than those for LTS/REBCO NMR magnet (see the
9 fourth column in TABLE IV). Therefore, tesseral harmonics are more easily corrected
10 by radial cryoshim coils for the LTS/Bi-2223 NMR magnet. The radial cryoshim coils
11 comprise sets of saddle-shaped coils, generating magnetic field in the transverse
12 direction, which is shielded by the screening current induced in the HTS coil. Therefore,
13 the radial cryoshim coil performance is notably weakened by the screening current.

14 Reduction of the performance of axial shim, such as Z, has been reported by Hahn et
15 al.³⁵ As seen in TABLE IV, the performance of axial cryoshim coils for Z1 and Z2 are
16 degraded to 36% and 22% of the theoretical design respectively for the LTS/REBCO
17 NMR magnet, while it is 61% and 64% for the LTS/Bi-2223 NMR magnet. As the
18 reduction is sufficiently low for the LTS/REBCO NMR, magnet zonal harmonics are
19 effectively corrected by cryoshim coils, while Z2 is eliminated by using ferromagnetic
20 shims.

21

22 **B. Remedies for improving the field homogeneity**

23 One potential fundamental remedy to correct field inhomogeneity for the
24 LTS/REBCO NMR magnet is to modify the REBCO conductors themselves. The
25 screening current-induced magnetic field intensity is nearly proportional to the width of
26 the REBCO layer³⁶. Therefore, if we could divide the REBCO layer into parts, i.e. a
27 multi-filamentary REBCO conductor,^{37,38} or use a smaller width conductor, the effect of

1 screening current will be several-fold reduced. The simulated performance of the Z2
2 cryoshim coil under the effect of screening current induced in the REBCO inner coil, as
3 a function of width of the REBCO conductor, is shown in FIG. 9. It improves with the
4 decrease in conductor width; e.g. it becomes 80.3% for 1 mm-width REBCO conductor,
5 better than the case of the LTS/Bi-2223 NMR magnet. The result also indicates that if
6 we could use a multi-filamentary REBCO conductor with a filament width of <1 mm,
7 similar excellent cryoshim performance is expected. However, multi-filamentary
8 REBCO conductors are still in the R&D stage and fabrication technology for long and
9 homogeneous conductors must be developed for commercially availability.

10 Another potential remedy is to improve the field correction methods. The first
11 problem to be solved is the presence of an enormous Z2 error harmonic due to the
12 reduction in the magnetic field generated by the outer field correction coil. To suppress
13 the effect of the screening current, we could use an inside notch type NMR magnet,³³
14 i.e. the field correction coils being installed in the innermost layer. Then, the effect of
15 the screening current on the field correction coil will be markedly reduced. As the inside
16 notch configuration reduces the central magnetic field intensity, an optimal magnet
17 design is necessary for super-high field NMR magnets. The second problem to be
18 solved is the occurrence of large tesseral error harmonics which cannot be effectively
19 corrected by cryoshim coils. The error harmonics are effectively corrected by
20 ferromagnetic shims installed inside the bore, working well under the effect of the
21 screening current in the REBCO winding. Though the correction field caused by
22 ferromagnetic shims fluctuates with time due to temperature instability, it is stabilized
23 by the ^2H field-frequency lock system and auto shimming system on various error
24 harmonics, as shown in this paper. We are preparing to develop an inside-notch type of
25 400 MHz LTS/REBCO NMR magnet, which will feature ferromagnetic shims installed
26 to counter the tesseral harmonics.

27

C. Further discussion; towards an ultra-compact LTS/REBCO NMR magnet operated beyond 1 GHz

Size of a magnet

The volume of an LTS high field NMR magnet steeply increases with magnetic field strength, as the Nb₃Sn inner coils are operated at a low conductor current density < 100 A/mm² above 20 T. Furthermore, a superfluid helium 2 K cooling system remarkably increases the magnet volume. On the other hand, HTS conductors have a high engineering critical current density > 200 A/mm² at 4.2 K in a magnetic field > 23 T.¹ A major advantage of REBCO conductors over Bi-2223 conductors is the higher tensile strength > 700 MPa, several-fold higher than that for Bi-2223 conductors (< 250 MPa). The tensile hoop stress for the coil winding is estimated to be $B_z jr$, where B_z is the axial magnetic field, j the current density for conductor cross section, and r the coil radius. Therefore a higher coil current density can be achieved if we use REBCO conductors; i.e. the NMR magnet size is in principle dramatically reduced. This idea is discussed in more detail in this section.

FIGURE 10(a) shows a cross section of the superconducting coils in the 1.03 GHz LTS/Bi-2223 NMR magnet installed in the National Institute for Materials Science. If we enhance the magnetic field to 1.2 GHz by using Bi-2223 inner coils with the maximum available hoop stress of 190 MPa, the NMR magnet becomes excessively large, as shown by the calculations of Otsuka and Kiyoshi in FIG. 10(b).⁷ The total weight of superconducting coils for the 1.2 GHz LTS/Bi-2223 NMR magnet design is 2.8-fold larger than that for the 1.03 GHz LTS/Bi-2223 NMR magnet, as shown in FIG. 10 and TABLE V. This is due to the lower conductor current density of < 120 A/mm² for the Bi-2223 coils, which are limited by the permissible hoop stress of 190 MPa.

On the other hand, FIG. 10(c) shows a design of a 1.2 GHz LTS/REBCO NMR magnet. It assumes an inner Z2 cryoshim REBCO coil; therefore, the inner diameter of the REBCO main coil is increased by 15 mm from the usual diameter of ~80 mm,

1 which is disadvantage to generate high magnetic field. The maximum permissible hoop
2 stress of REBCO coils was assumed to be 488 MPa, which enables a conductor current
3 density of 272 A/mm^2 . The total weight of superconductors for the 1.2 GHz
4 LTS/REBCO NMR magnet is 16-fold smaller than that of the 1.2 GHz LTS/Bi-2223
5 NMR magnet, as seen in TABLE V. The size of a 1.2 GHz LTS/REBCO NMR magnet
6 becomes comparable to that of a conventional 700-800 MHz NMR magnet. Thus, these
7 calculations demonstrate that an ultra-compact size super-high field NMR is possible if
8 we take advantage of REBCO conductors, thereby driving a paradigm change in super-
9 high field NMR magnets. For high current density operation, magnet protection from
10 thermal runaway^{24,25,26} is of significance for safe operation of the magnet.

11 Recently, stronger Bi-2223 conductors with a tensile strength of 450~500 MPa
12 have been developed.³⁹ It is probable that an ultra-compact type super-high field NMR
13 magnet might be similarly achieved using this new type of Bi-2223 conductors. As the
14 effect of screening current on the magnetic field stability and homogeneity for the
15 LTS/Bi-2223 NMR magnet is 1/10 of those for the LTS/REBCO NMR magnet, Bi-
16 2223 might be a better candidate over REBCO. Further investigations are being made in
17 this regard.

18 ***Possibility of a self-persisting magnet operation***

19 Conventional LTS NMR magnets are operated in a persistent current mode; i.e. the
20 magnets are self-persisting without an external power supply after they are charged.
21 Joining technologies for conductors with a joint resistance $<10^{-10} \Omega$, so-called
22 persistent-joints or superconducting-joints,⁴⁰ for LTS-to-LTS enable the persistent
23 current mode operation. Currently, there is no practical superconducting joint
24 technology for HTS-to-HTS and HTS-to-LTS and thus external current mode operation
25 is inevitable for LTS/HTS NMR magnets as shown in this paper.

26 Recently, new methods for superconducting joints have been proposed^{41,42} for
27 REBCO conductors. If those methods become practical, a self-persisting LTS/REBCO

1 NMR magnet might be feasible; for this purpose, further investigation must be made on
2 (a) the mechanical integrity and reasonable heat treatment time of the joint, and (b) a
3 long REBCO conductor with a piece length of >1 km.

4 On the other hand, a superconducting joint for Bi-2223 and Bi-2212 conductors has
5 not been developed so far. Furthermore, these conductors intrinsically show a slight
6 normal resistivity⁴³ even though the coil is operated at far below its critical current.⁴⁴
7 Therefore, it is unlikely that LTS/Bi-2223 or LTS/Bi-2212 NMR magnets will be able
8 to be operated in the persistent mode; i.e. they will be operated in the external current
9 mode.

11 **V. Conclusions**

12 The world's first LTS/REBCO NMR spectrometer has been developed and operated
13 at 400 MHz. It is a first step towards an ultra-compact super-high field NMR magnet
14 operated at frequencies beyond 1 GHz. Based on measurements of temporal magnetic
15 field stability, spatial magnetic field homogeneity, and NMR spectra, the particular
16 characteristics of the LTS/REBCO NMR magnet have been clarified. They are
17 summarized as follows.

- 18 (1) A layer-wound inner coil for NMR magnets was fabricated using very thin tape
19 REBCO conductors by a technique of jointing conductors during winding, control
20 of winding diameter during winding, and paraffin wax impregnation. The coil was
21 installed in the NMR magnet and it was successfully charged without degradation
22 in performance.
- 23 (2) Magnetic field drift with time due to relaxation of the screening current induced in
24 the REBCO inner coil of LTS/REBCO NMR magnet is significantly high. The time
25 duration to reach a drift rate of 0.01 ppm/h, required for ^2H lock operation, was
26 estimated to be ~ 600 days, which is impractically long. A current sweep reversal as
27 large as 10% of the peak current removed the drift.

- 1 (3) The screening current induced in the REBCO inner coil substantially reduced the
2 magnetic field generated by the outer field correction coils. This results in the
3 emergence of a substantial Z2 harmonic which cannot be compensated by a
4 cryoshim coil. The error harmonic was sufficiently corrected using ferromagnetic
5 shims.
- 6 (4) For the LTS/REBCO NMR magnet, large tesseral-harmonics such as ZY, C2 and
7 S2 occur. The harmonics cannot be effectively corrected by cryoshim coils due to
8 the reduction of the performance of the cryoshim coils caused by the screening
9 current. Therefore, the NMR resolution and sensitivity for the LTS/REBCO NMR
10 magnet was ten-fold lower than those for a conventional LTS NMR magnet.
- 11 (5) A 2D HSQC spectrum for a chlorella ubiquitin was obtained for the LTS/REBCO
12 NMR magnet operated at 400 MHz. To achieve sufficient water suppression and
13 multi-dimensional NOESY, further correction of the field inhomogeneity caused by
14 tesseral-harmonics is required.
- 15 (6) An ultra-compact 1.2 GHz NMR is possible if we effectively take advantage of the
16 REBCO conductor, even though it has the disadvantage of an enormous screening
17 current-induced magnetic field. Further investigation should be made on the multi-
18 filamentary REBCO conductor and intensive field correction methods. Recently
19 developed high-strength Bi-2223 conductors might be another candidate for a 1.2
20 GHz NMR.

21

22 **Acknowledgments**

23 This research was supported by the Japan Science and Technology Agency, JST,
24 under the Strategic Promotion of Innovative Research and Development Program and
25 under SENTAN.

26 The authors would like to express our gratitude to the late Tsukasa Kiyoshi (1959-
27 2013), for his outstanding and distinguished contributions to the area of high field
28 magnet technology, including the project described in the present paper.

29 The authors thank T. Higo of Yokohama City for the sample preparation.

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- 3
- 4

1 **Table captions:**

2 **TABLE I.** Physical parameters of the LTS/REBCO NMR magnet operated at 400 MHz
3 (9.39 T)

4

5 **TABLE II.** Measured field error harmonics for the LTS/REBCO NMR operated at 400
6 MHz (9.39 T)

7

8 **TABLE III.** Measured field error harmonics for the LTS/Bi-2223 NMR operated at 500
9 MHz (11.7 T). Before the cryoshim coils correction, the Z1 cryoshim coil was charged
10 to -7 A to improve the sensitivity for the field mapping unit.

11

12 **TABLE IV.** Correction capability of cryoshim coils for the LTS/REBCO NMR magnet
13 operated at 400 MHz (9.39 T) and for the LTS/Bi-2223 NMR magnet operated at 500
14 MHz (11.7 T).

15

16 **TABLE V.** Major parameters for (a) the 1.03 GHz LTS/Bi-2223 NMR magnet, (b) the
17 design of the 1.2 GHz LTS/Bi-2223 NMR magnet,⁷ (c) the design of the 1.2 GHz
18 LTS/REBCO NMR magnet.

19

20

Figure captions:

FIGURE 1. LTS/REBCO NMR magnet operated at 400 MHz (9.39 T).

FIGURE 2. (a) Hysteresis of the screening current-induced magnetic field, B_s , for LTS outer coils + REBCO inner coil (black solid line) and for REBCO inner coil (blue dashed line). B_s was obtained by subtracting the calculated coil magnetic field from the actual magnetic field. First, both LTS outer coils and REBCO inner coil were charged in the positive polarity (curve-1 and curve-2) and discharged (curve-3). Second, the REBCO inner coil was independently charged in the negative polarity (curve-4) and discharged (curve-5). Then, it was charged in the positive polarity (curve-6) and discharged (curve-7). Finally, it was charged in the negative polarity (curve-8) and discharged (curve-9) once again. (b) Hysteresis of the screening current-induced magnetic field for the LTS outer coils + Bi-2223 inner coil (black solid line) and for Bi-2223 inner coil (blue dashed line). B_s was obtained by subtracting the calculated coil magnetic field from the actual magnetic field. First, both LTS outer coils and Bi-2223 inner coil were charged in the positive polarity (curve-1) and discharged (curve-2). Then, the Bi-2223 inner coil was independently charged and discharged in both positive and negative polarities several times. Curves-3 to -6 show a cycle of the charge/discharge process.

FIGURE 3. (a) Temporal drift of the central magnetic field for the LTS/REBCO NMR magnet operated at ~ 500 MHz, after achieving the operating current. Black solid line: without current sweep reversal. Blue dashed line: with current sweep reversal by 5%. Red dashed-dotted line: with current sweep reversal by 12%. (b) Temporal drift of the central magnetic field for the LTS/Bi-2223 NMR magnet operated at ~ 500 MHz. Black solid line: without current sweep reversal. Blue dashed line: with current sweep reversal by 1%. The graph was reproduced based on data provided in ref. [10].

FIGURE 4. (a) Spatial magnetic field distribution along the z -axis for the LTS/REBCO NMR magnet operated at ~ 500 MHz measured by an NMR Teslameter. (b) Magnetic field distribution along the z -axis for the LTS/Bi-2223 NMR magnet operated at ~ 500 MHz.¹⁰ The distribution represented by the dashed line is reproduced based on field harmonics obtained by a field mapping system.

FIGURE 5. Spatial magnetic field distribution along the z -axis for the LTS/REBCO NMR magnet operated at ~ 400 MHz. Open circles show the distribution without

ferromagnetic shim operation. Closed triangles show the distribution with ferromagnetic shim operation to reduce the Z2 harmonic.

FIGURE 6. Results of ^1H line shape test for 1% chloroform in acetone- d_6 for the LTS/REBCO NMR magnet operated at 400 MHz. (a) NMR spectrum obtained under 20 Hz sample spinning, obtained by a single scan. The half height line width is 0.3 Hz, while those for 0.55% and 0.11% of the main peak are 10 Hz and 40 Hz, respectively. (b) NMR spectrum obtained without sample spinning for the 400 MHz LTS/REBCO NMR magnet, obtained by a single scan. The half height line width is 15 Hz, while those for 0.55% and 0.11% of the main peak are as large as 235 Hz and 286 Hz, respectively.

FIGURE 7. ^1H NMR sensitivity test result for 0.1% ethylbenzene in CDCl_3 for the 400 MHz LTS/REBCO NMR magnet, obtained by a single scan under sample spinning of 20 Hz. Signal to noise ratio is 28.2 based on the ratio between the central peak of the quartet at 2.7 ppm and the noise over 0.4 pp.

FIGURE 8. (a) ^{15}N - ^1H HSQC spectrum for 1.2 mM ^{13}C - and ^{15}N -labeled chlorella ubiquitin in 80% H_2O and 20% D_2O obtained by the LTS/REBCO NMR magnet operated at 400 MHz. (b) ^{15}N - ^1H HSQC spectrum for 2 mM ^{13}C - and ^{15}N -labeled chlorella ubiquitin in 90% H_2O and 10% D_2O obtained by a conventional 500 MHz LTS NMR magnet. For both measurements, the number of signal points along the t_2 axis, the number of signal points along t_1 axis, number of scans and measurement time interval were 1024, 64, 64 and ~ 1.2 h. The red dashed circles show NMR signals which are not seen in Figure. 8(a).

FIGURE 9. Simulated performance of the Z2 cryoshim coil under the effect of the screening current for the REBCO inner coil, as a function of the REBCO conductor width. Open circles show reduced Z2 harmonic when the Z2 cryoshim coil is charged to 20 A under the effect of the screening current. Dashed line shows designed Z2 harmonic of the Z2 cryoshim coil performance for 20 A. The left vertical axis shows Z2 harmonic in unit of Hz/cm^2 , while the right axis the ratio of $Z2_{\text{red.}}$ to $Z2_{\text{desgn.}}$. The simulation was made by the method described in ref. [19]. Note that effect of full penetration of the magnetic field to a superconductor, i.e. a saturation effect, is neglected in the present simulation and therefore it is the worst case analysis.

1 **FIGURE 10.** Cross sectional view of NMR magnets for (a) the 1.03 GHz LTS/Bi-2223
2 NMR magnet installed in the National Institute for Materials Science, (b) a design of a
3 1.2 GHz LTS/Bi-2223 NMR magnet with hoop stress limit of 190 MPa,⁷ (c) a design of
4 a 1.2 GHz LTS/REBCO NMR magnet with hoop stress limit of 500 MPa.
5

Table I

	Unit	REBCO inner coil	Overall coils
Conductor cross section (width $\times$ thickness)	mm $\times$ mm	5 $\times$ 0.15	-
Insulated conductor cross section (width $\times$ thickness)	mm $\times$ mm	5.1 $\times$ 0.25	-
Inner diameter of coil winding	mm	81.3	81.3
Outer diameter of coil winding	mm	118.7	331.75
Length of coil winding	mm	400	546
Number of layers	-	72	206
Number of turns	-	5532	42028
Conductor length	m	1729	29134
Operating current	A	109.3	109.3
Central magnetic field	T	1.86	9.39
Conductor current density	A/m ²	146	-
Winding current density	A/m ²	80.9	-
Maximum hoop stress	MPa	65.2	-
Load factor	-	0.28	-

Table II.

Harmonics	Before cryoshim correction (Map no. 151)		After cryoshim correction (Map no. 196)	
	Cryoshim coil current (A)	Amplitude of error harmonics (Hz/cm ⁿ)	Cryoshim coil current (A)	Amplitude of error harmonics (Hz/cm ⁿ)
Z1	0 A	195	1 A	1484
Z2	0 A	-1175	-20 A	-475
X	0 A	-833	20 A	-2
Y	0 A	-327	-4 A	295
ZX	0 A	241	20 A	252
ZY	0 A	-3208	20 A	-2541
C2	0 A	-3563	-20 A	-2998
S2	0 A	983	20 A	832

Table III.

Harmonics	Before cryoshim correction (Map no. 19)		After cryoshim correction (Map no. 104)	
	Cryoshim coil current (A)	Amplitude of error harmonics (Hz/cm ⁿ)	Cryoshim coil current (A)	Amplitude of error harmonics (Hz/cm ⁿ)
Z1	-7 A	1058	-6 A	-143
Z2	0 A	209	3 A	1258
X	0 A	-814	-6 A	495
Y	0 A	-9705	15.7 A	152
ZX	0 A	-953	3 A	64
ZY	0 A	-1317	6 A	-76
C2	0 A	-238	-2 A	45
S2	0 A	642	0 A	33

Table IV.

Harmonics	Design correction capability of cryoshims for 20 A (Hz/cm ⁿ)	Efficiency in LTS/REBCO NMR magnet	Efficiency in LTS/Bi-2223 NMR magnet
Z1	115780	36%	61%
Z2	2800	22%	64%
X	35480	4.1%	15%
Y	35480	2.2%	35%
ZX	7640	0.6%	25%
ZY	7640	0.3%	25%
C2	4400	4.6%	-
S2	4400	3.6%	-

Table V.

	Unit	(a) 1.03 GHz LTS/Bi-2223 NMR	(b) 1.2 GHz LTS/Bi-2223 NMR design	(c) 1.2 GHz LTS/REBCO NMR design
Magnetic field	MHz / T	1.03 / 24.2	1.2 / 28.2	1.2 / 28.2
Maximum hoop stress	MPa	188	190	454
Self inductance	H	1139	-	837.8
Stored energy	MJ	33.9	147	10.1
Radial distance from the center to 0.5 mT line	m	10.8	16.6	6.5
Axial distance from the center to 0.5 mT line	m	13.7	21.0	8.3
Weight of HTS conductors	kg	42.8	212	461
Total weight of superconductors	kg	4754	12945	797

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

graphical abstract