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Development of a 700 MHz low-/high- temperature superconductor nuclear magnetic resonance magnet: Test results and spatial homogeneity improvement

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Abstract

For the first time in nuclear magnetic resonance (NMR) magnet development, a magnet configuration comprising an insert wound with high-temperature superconductor (HTS) and a background-field magnet wound with low-temperature superconductor (LTS) has been proven viable for NMR magnets. This new LTS/HTS magnet configuration opens the way for development of 1 GHz and above NMR magnets. Specifically, a 700 MHz LTS/HTS NMR magnet (LH700), consisting of a 600 MHz LTS magnet (L600) and a 100 MHz HTS insert (H100), has been designed, built, and successfully tested, and its magnetic field characteristics were measured and analyzed. A field homogeneity of 172 ppm in a cylindrical mapping volume of 17 mm diameter by 30 mm long was measured at 692 MHz and corresponding ¹H NMR signal with 1.9 kHz half-width was captured. Two techniques, room-temperature and ferromagnetic shimming, were analytically examined to investigate if they would be effective for further improving spatial field homogeneity of the LH700.

This paper reports on a world-first low-/high-temperature superconductor (LTS/HTS) 700 MHz nuclear magnetic resonance (NMR) magnet (LH700), designed, built, and successfully tested at the MIT Francis Bitter Magnet Laboratory (FBML). In the LH700, a 100 MHz HTS insert (H100) was placed in the cold bore of a 600 MHz LTS magnet (L600). Although a 950 MHz all-LTS NMR magnet is the latest achievement,¹ it is generally agreed among magnet engineers that 1 GHz is the practical frequency limit for all-LTS NMR magnets. We believe that the HTS capable of functioning at magnetic fields substantially greater than those of the LTS will play an increasingly prominent role in NMR magnets with operating frequency of 1 GHz and above.

The key design philosophy adopted for the H100 includes (1) use of Bi2223-Ag composite tape and (2) a magnet configuration of stacked double-pancake (DP) coils—both for the first time in the history of NMR magnet development. Advantages of the DP coil-based HTS insert include (1) a conductor length typically required, <~200 m, for one DP coil is much less than that necessary, >5000 m, for its layer-wound counterpart, because it is much easier to obtain HTS tape meeting design specifications in short rather than long lengths; (2) DP-coil assembly permits placement of each DP coil, at an axial position within the insert assembly, according to the B_{ext} versus I_c characteristics of an individual DP coil that are most favorable to its current-carrying capacity, thereby maximizing the overall critical current density; (3) axial space between adjacent DP coils may be varied for field profiling with spacers of different thicknesses

between DP coils; and (4) in a DP-coil assembly, only defective DP coils need to be replaced rather than the entire insert, as it would be with a layer-wound insert.

The H100 consisted of 48 DP coils, each wound with stainless steel reinforced Bi2223-Ag three-ply tape manufactured by American Superconductor Corp. (AMSC). Every DP coil in the H100 was wound in house, with a winding machine² designed and built in the FBML. For the L600, a 600 MHz NMR-quality LTS magnet was purchased from Japan Superconducting Technology Inc. The L600 is equipped with superconducting shim coils up to the second order, three axial (Z0, Z1, and Z2) and six radial (X, Y, ZX, ZY, XY, X2–Y2) coils. During the LH700 test at 692 MHz, the L600 was operated at 235 A in persistent mode, while the H100 at 116 A in driven mode.

Figure 1 shows a schematic to-scale drawing of the LH700; H100 is to be installed in the cold bore of L600. In the actual test, the magnetic center of LH700 was defined by the center of Z, X, and Y shim coils, where both centers of H100 and L600 were aligned. The LH700 is housed in a cryostat with a separate 54 mm room-temperature bore for a NMR probe insertion from the top. Further mechanical features as well as details of the LH700 have been previously reported.^{3–5}

For field mapping, a 0.7 μ l sample ¹H NMR probe was traced along a helical path over a cylindrical surface of 17 mm diameter and 30 mm long in 12 revolutions. More than 256 points were acquired and statistically analyzed. Table I presents the measured field gradients, up to the fourth order; the number in parenthesis is the standard deviation of each gradient that corresponds to its temporal stability. The comparison of field gradients between L600 and LH700 proves that most field errors of LH700 originated in the H100. The dominant field gradients of LH700, Z, Y, and ZY, were reproducible. The final field homogeneity of LH700 at 692 MHz was 172 ppm over the cylindrical mapping volume of 17 mm diameter by 30 mm long.

Two techniques to further improve the LH700 field homogeneity were examined: (1) a set of room-temperature “shim coils” (RT shim coils); and (2) the so-called ferroshimming, entailing a set of ferromagnetic tiles mounted on the cylindrical surface of the RT bore.

First, RT-shim coils, parameters of which are summarized in Table II, were designed to cancel three major field gradients, Z, Y, and ZY (Table I). The power consumption of each set of shim coils is less than 10 W, within the limit of natural convective cooling available in the magnet bore.

Next, we designed, in cooperation with Resonance Research Inc. (RRI), a ferroshimming set to be mounted over a cylindrical surface of the 54 mm diameter RT bore tube. It consists of a grid of 480 ferromagnetic tiles, each 25.4 μ m thick, 8 mm wide in the azimuthal direction, and 3 mm long in the axial direction, with a saturation magnetization of 2.1 T. These tiles are used routinely by RRI in ferroshimming of high homogeneity NMR magnets.

Figure 2 shows axial distance versus frequency difference plots for the LH700 at 692 MHz; the open circles and the dashed line are, respectively, measured and computed (based on an analytical model⁶); the dotted line corresponds to the case with the RT shim coils alone activated under an assumption that they would remove only 80%, though 100% in design, of the three major (Z, Y, ZY) error components shown in Table I; the solid line is the one with the ferroshimming set alone in effect—the resulting field gradients are summarized in Table I. Each shimming technique clearly improves the field homogeneity over the same 17 mm diameter by 30 mm long cylindrical volume: with the RT shimming and without ferroshimming, it is 39 versus 172 ppm with only superconducting shim coils of the L600 charged; with the ferroshims it is 7 ppm.

Figure 3 shows the same results as normalized NMR signal versus frequency difference plots. Here the original half-width of 1.9 kHz (solid line) is reduced to 385 Hz with the RT shimming alone (dashed line) and to 37 Hz (dotted line) with the ferrosims alone. To conclude, it has been demonstrated that if both techniques are applied to the LH700, with each technique optimized for this combined case, the half-width at 692 MHz would be reduced to less than 37 Hz and a field inhomogeneity to less than 7 ppm.

A world-first 700 MHz LTS/HTS NMR magnet (LH700), consisting of a 600 MHz LTS magnet and a 100 MHz HTS insert, has been designed, constructed, and successfully tested, and their magnetic field characteristics were measured and analyzed. The LH700 represents a new class of NMR magnet configuration, i.e., a LTS background magnet with a HTS insert, specifically targeted to reach and exceed an operating frequency of 1 GHz. Based on results generated to date by the LH700, we may conclude the following.

- The magnet configuration comprising a stack of DP coils, each wound with high-strength Bi2223-Ag tape, has been proven viable for application to LTS/HTS NMR magnets.
- Most field errors, in terms of spatial homogeneity and temporal stability, were generated by the H100. Field homogeneity of 172 ppm at 692 MHz was measured over the cylindrical mapping volume of 17 mm diameter by 30 mm long, and corresponding NMR signal with 1.9 kHz half-width was captured.
- Two shimming techniques were investigated, i.e., a set of RT shimming coils and a ferrosimming set that, even when each operated alone, were effective in improving the field quality of the LH700 and will likely be with those operating at 1 GHz and above; for example, a ferrosimming set alone enables the LH700 to achieve a NMR signal half-width of ~40 Hz at an operating frequency of 692 MHz, corresponding to a field homogeneity of 7 ppm in the 17 mm diameter and 30 mm long cylindrical volume.

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FIG. 1.
(Color online) Schematic to-scale drawing of LH700; H100 is to be installed in the cold bore of L600. All dimensions are in millimeters.

FIG. 2.

Axial distance vs frequency difference plots for the LH700 at 692 MHz; open circles: measured data; solid line: calculated based on an analytical model; dashed line: calculated with the RT shim alone activated; dotted line: calculated with ferroshimming set alone in effect.

FIG. 3. Normalized NMR signal vs frequency difference plots; solid line: measured; dashed line: with the RT shim coils alone activated; dotted line: with the ferroshim set alone in effect.

TABLE I

Measured field gradients up to the fourth order: (1) L600 at 588 MHz; (2) LH700 at 692 MHz; (3) calculated LH700 map after a ferroschim set applied on the LH700 map (without RT-shim).

Gradients	L600	LH700	LH700 (ferroschim)
Z^a	2301 (30)	18009 (413)	-324
ZZ^b	8454 (39)	4734 (515)	-427
$Z3^c$	-1416 (46)	-131 (629)	144
$Z4^d$	-312 (62)	-90 (824)	208
X^a	-605 (52)	442 (712)	349
Y^a	168 (51)	18927 (709)	80
ZX^b	1358 (78)	-1101 (1068)	161
ZY^b	-376 (77)	29242 (1049)	-1328
$C2^b$	-961 (63)	-2148 (873)	245
$S2^b$	-523 (63)	-1136 (871)	-108
$Z2X^c$	-13 (60)	-1158 (821)	91
$Z2Y^c$	221 (58)	-5800 (780)	-355
$ZC2^c$	-79 (53)	-367 (730)	-612
$ZS2^c$	36 (53)	-896 (724)	-308
$C3^c$	115 (54)	501 (743)	395
$S3^c$	114 (54)	307 (747)	115
$Z3X^d$	85 (81)	3384 (1101)	115
$Z3Y^d$	144 (75)	-2495 (991)	494
$Z2C2^d$	138 (69)	55 (944)	887
$Z2S2^d$	68 (69)	1074 (923)	-599
$ZC3^d$	196 (62)	-511 (844)	243
$ZS3^d$	-177 (62)	43 (859)	429

^a [Hz/cm].

^b [Hz/cm²].

^c [Hz/cm³].

^d [Hz/cm⁴].

TABLE II

Parameters of Z, Y, and ZY RT shim coils; r_0 radius of loop (Z) or arc (Y and ZY); z_0 : axial location of loop (Z); z_1 and z_2 : axial locations of one set of four saddles (Y and ZY). (Units: Hz/cm for Z and Y; Hz/cm² for ZY.)

Parameters	Z	Y	ZY
Strength	20 000	20 000	30 000
layers; turns	2;14	2;12	4;14
r_0 (mm)	25.4	20.9	23.0
z_0 (mm)	22.0	...	...
$z_1 ; z_2$ (mm)	...	8.2; 47.7	15.6; 58.8
Total wire (m)	9	18	47
Resist (Ω)	1.20	2.29	6.27
Current (A)	1.34	0.93	1.14
Power (W)	2.15	1.97	8.17