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Field Performance of an Optimized Stack of YBCO Square “Annuli” for a Compact NMR Magnet

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Abstract

The spatial field homogeneity and time stability of a trapped field generated by a stack of YBCO square plates with a center hole (square “annuli”) was investigated. By optimizing stacking of magnetized square annuli, we aim to construct a compact NMR magnet. The stacked magnet consists of 750 thin YBCO plates, each 40-mm square and 80- μm thick with a 25-mm bore, and has a $\varnothing 10$ mm room-temperature access for NMR measurement. To improve spatial field homogeneity of the 750-plate stack (YP750) a three-step optimization was performed: 1) statistical selection of best plates from supply plates; 2) field homogeneity measurement of multi-plate modules; and 3) optimal assembly of the modules to maximize field homogeneity. In this paper,

we present analytical and experimental results of field homogeneity and temporal stability at 77 K, performed on YP750 and those of a hybrid stack, YPB750, in which two YBCO bulk annuli, each Ø46 mm and 16-mm thick with a 25-mm bore, are added to YP750, one at the top and the other at the bottom.

Index Terms

Compact NMR; field cooling; field homogeneity; optimization; temporal stability; trapped field; YBCO plates

I. Introduction

AN NMR magnet comprised of superconducting cylinders or a stack of superconducting plates has been studied since 1980s [1], [2]. A two-year program to develop a 100–200 MHz compact NMR magnet was began 2009 at the Francis Bitter Magnet Laboratory, MIT [3]–[6]. Key design concepts include: 1) use of a stack of YBCO plates with a bore; 2) field cooling with a homogeneous background electromagnet to induce a trapped field; 3) use of solid cryogen, nitrogen or neon, operated at 10–15 K. The first pilot magnet (YP500) which consisted of 500 YBCO thin plates—each, 40 mm square and 0.08 mm thick with a 25 mm center hole—was constructed and tested in 2009 [6]. A peak trapped field of 0.19 T was achieved at 77 K and 2.3 T at 4.2 K [6]; the later corresponds to a 98 MHz NMR frequency.

This year a new stack magnet was designed and constructed with YBCO plates of better critical current density. A total of 750 plates were stacked (YP750) and a three-step optimization was performed to improve field homogeneity: 1) statistical collection of the best plates from supply plates; 2) construction and field homogeneity measurement of multi-plate modules to select the best stack pattern; and 3) assembly of an optimized module stack. We present and analyse the homogeneity and temporal stability of a trapped field, at 77 K, of YP750 and those of a hybrid stack, YPB750, in which two YBCO bulk annuli, each Ø46 mm and 16-mm thick with a 25-mm bore, are added to YP750, one at the top and the other at the bottom.

II. Optimization of YBCO Plate Stack

A. Collecting Best Plates

One clear advantage of a stack magnet is that only best plates, out of many plates, may be selectively used to assemble it. Since 2007, American Superconductor Corp. (AMSC) has provided 1500 coated YBCO plates, 40-mm square 80- μ m thick, cut from 40-mm wide coated YBCO tape that AMSC manufactures and slits it to produce 4-mm wide standard conductor. With an assumption of a continuous critical current density of a 40-mm wide tape in the longitudinal direction, we applied a statistical analysis to select 850 best plates out of 1500 plates from the measured results of 50 sampling plates.

Among the 850 plates, three plates—#216, #244, #382—were tested with a 5-T/300-mm room-temperature bore background magnet [6] before and after a center hole was created to check if the boring process (machining) had caused any degradation. Table I summarizes test and calculation results and Fig. 1 presents surface field mappings of the sample #382 measured at 2 mm above the plate surface, confirming no degradation in these plates. Very few plates were degraded by the boring process and their trapped fields with a hole were less than 1 mT. In calculation, a nonlinear 2-D finite element method and the Bean critical state model were used [6].

B. Multi-Plate Module With Two Stack Orientations

A single module consists of 25 plates randomly chosen from the 850 plates. In stacking these square plates, we tested two orientations, as shown in Fig. 2: (a) orthogonal square (Square), in which two orthogonal edges of each square, one along the transport current direction (the original tape axis) and perpendicular to it are alternated from one plate to the next; (b) polygon-star (Star), in which a current-direction edge is rotated by 22.5° from one plate to the next, the same orientation as that of the YP500 studied in 2009 [6]. A 0.1-T NdFeB permanent magnet disk, $\varnothing 63.5$ mm and 6.4-mm thick, was used to field-cool each 2-mm thick (25 plates) module. Fig. 3 shows a sample holder and a LN_2 container, designed to precisely align a module and the permanent magnet with a 3-mm axial distance between the two nearest surfaces.

After field cooling and the permanent magnet removed, a 10-min. waiting period was allotted to precisely control the moment at which field mapping of each module could begin. Then, axial-field mapping was performed along the module axis at every 1-mm increment, followed by surface mapping at 2 mm above the module top surface; the Hall sensor has a half thickness of 1 mm. A surface field mapping covers a 6×6 mm area at every 0.5 mm in x- and y-directions. Three modules, each with the two orientations, were tested; Table II presents peak axial field data. Each test was repeated twice and reproducibility of mappings was confirmed ($<1\%$ error). In all tests, the Square module trapped a higher field than the Star. Fig. 4 presents two surface mappings of the module #3: (a) Square and (b) Star. Radial homogeneity and field lines of each stack pattern are similar to each other.

C. Optimized Stack Order of Multi-Plate Modules

With the Square orientation, 34 25-plate modules were constructed from the 850 plates. The trapped field of every module was measured with the permanent magnet and the measurement devices in Fig. 3. Among the 34 modules, 10 modules (YP250) were randomly selected and stacked in two different orders: 1) “Linear” in which the worst module (in terms of trapped field strength) at the bottom and progressively to the best module at the top; and 2) “Optimized” (for field homogeneity) in which the best module is at the center and progressively to the worst module at each end. The YP250 was field-cooled with a field of 0.11 T, 50% of its full trapped field capacity when it was saturated in a separate test.

Fig. 5 shows trapped field distributions along the YP250 axis: Linear (red triangles); and Optimized (black squares). Although the peak field of Linear is larger than that of Optimized by 8%, the axial homogeneity of Optimized in $|z| < 2$ mm, 1.5%, is better than that of Linear, 4.7%. Fig. 6 compares surface mappings at 2 mm above the top of YP250: a) Optimized at the YP250 geometric center ($z = 0$ mm in Fig. 5); b) Linear at the peak field location ($z = 3$ mm in Fig. 5). Note that the radial homogeneity of Optimized within $|r| < 1$ mm range is 0.092%, while that of Linear is 0.15%.

Fig. 7 provides two-hour temporal decay traces of the trapped fields shown in Fig. 6 Linear (red triangles) and Optimized (black squares). The average decay of Linear, 4.6% per hour, is faster than that of Optimized, 3.2% per hour.

III. Tests of YP750 and YPB750

Fig. 8 shows two pictures of test magnets: (a) YP750 assembled from 30 25-plate modules in an optimized stacking order; and (b) YPB750 where two extra YBCO bulk annuli are placed at the top (Bulk T) and bottom (Bulk B) of the YP750. The i.d., o.d, and thickness of each bulk annulus are 25, 46, and 16 mm, respectively. The center trapped fields of Bulks T and B are 0.25 and 0.21 T, respectively, when the bulks are fully saturated. The overall stack height of the YP750 is 60 mm.

For field-cooling, a 5-T background magnet was discharged at a rate of 1 mT/s [6]. From the moment the background magnet was completely discharged, the trapped field was measured, first its temporal function for a period of two hours, followed by mapping of its axial and radial field distributions.

Fig. 9 shows axial trapped field vs. axial distance plots for YP750 and YPB750, each field-cooled from two background fields, 0.75 T and 0.25 T. As background field was reduced from 0.75 to 0.25 T, the center zone field homogeneity improved. The axial fields of YP750 are fairly symmetric in both 0.25 T and 0.75 T tests, while YPB750 the 0.75 T field profile is not. This is because of a discrepancy in trapped fields in full saturation, 0.25 T vs. 0.21 T, between Bulks T and B. Note that in the 0.25 T test, the center field profiles of YP750 and YPB750 are almost identical and much more uniform than those in the 0.75 T tests. Table III summarizes axial and radial field errors from a harmonic analysis, where Z_1 , Z_2 , Z_3 , Z_4 , e_z , and e_g are the first, second, third, fourth order axial gradients, overall axial and radial field errors in $|z| < 2$ mm and $|r| < 1$ mm, respectively. Note that the field gradients of both magnets are similar to each other except the Z_4 ; overall field distribution of the 0.25-T YP750 in the $|z| > 20$ mm region in the Fig. 9 is convex while that of the YPB750 is concave. This implies that the two bulk annuli may help to improve field homogeneity by reducing high-order axial field gradients. On the other hand, low-order axial gradients are mostly dictated by the uniformity of the plates in the midplane region.

Fig. 10 presents temporal decays of the axial center fields in Fig. 9. In general, a higher trapped field corresponds to a faster temporal decay. Overall decay patterns of the two magnets are similar. Note that the decay rate of the 0.25-T YP750 was 101 ppm/hr at beginning and in two hours it dropped to 28 ppm/hr.

Fig. 11 shows surface field distributions over the magnet center zone at different axial points in Fig. 9: (a) 0.75-T YP750 at $z = 3$ mm; (b) 0.25-T YP750 at $z = 0$ mm; (c) 0.75-T YPB750 at $z = -2$ mm; (d) 0.25-T YPB750 at $z = 0$ mm. Note that the overall radial field errors of 0.75-T tests are $\sim 1\%$ over the center area of 7×7 mm while those of 0.25-T tests are only $\sim 0.2\%$.

IV. Conclusion

A stacking optimization for improved field homogeneity was applied to build a compact NMR magnet from a stack of 750 YBCO plates. The optimization consists of three steps: 1) statistical collection of the best plates from supply plates; 2) construction and test of each multi-plate module with the best stack pattern; and 3) stacking the modules in an optimized order to achieve the best field homogeneity. Two stack magnets, YP750 and YPB750, were tested, at a field-cooling temperature of 77 K, for axial and radial field homogeneities and temporal stability; YP750, an optimized assembly of 30 25-plate modules and YPB750, a hybrid stack, in which two YBCO bulk annuli are added to YP750, each at the top and the bottom.

Field-cooled at 0.75 T, peak trapped fields were 0.42 and 0.44 T, respectively, for YP750 and YPB750. In general, spatial homogeneity and temporal stability improve with decreasing trapped field, i.e., when field-cooled at lower fields. At a trapped field of 0.21 T, the overall axial and radial homogeneities of YP750 are 471 and 110 ppm in $|z| < 2$ mm and $|r| < 1$ mm while those of YPB750 are 520 and 74 ppm, respectively. The axial field gradients of the two magnets in the magnet midplane region are similar to each other up to the fourth order except the Z_4 , which may imply that low-order axial gradients are chiefly dictated by the uniformity of the plates in the midplane region and the high-order gradients may be reduced with bulk annuli far from the midplane region. The temporal stability of

YP750 at 0.21 T trapped field was 101 ppm/hr at the beginning of measurement, decreasing to 28 ppm/hr in two hours. In 2009, YP500 reached 2.3 T at 4.2 K with a background field of 5 T and 0.19 T at 77 K with a background field of 0.3 T [6].

Based on the measured results obtained over the past one year, we are quite confident that a compact NMR magnet in the frequency range 100–200 MHz (trapped field range 2.35–4.70 T) is achievable in the very near future. Currently, a new test setup is being prepared in which a combination of liquid helium and solid nitrogen will be used to permit field-cooling in the range 4.2–15 K.

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Fig. 1. Surface field mappings of the sample #382 measured at 2 mm above the plate surface: before (a) and after (a) a hole was created. All units in mT.

Fig. 2.
Top views of two 25-plate stacking orientations: (a) orthogonal square (Square); (b) polygon star (Star).

Fig. 3.

(a) Sample holder in a LN_2 container; (b) LN_2 container bottom with a recessed circular space for holding a permanent magnet disk. This system was used for the individual plate tests and the 25-plate module tests.

Fig. 4. Surface field mappings of the module #3 measured at 2 mm above the module top surface: (a) Square; (b) Star. All units are in mT.

Fig. 5. Trapped field distributions along the axis of YP250; red triangles: linear; black squares: optimized.

Fig. 6. Surface field mappings at 2 mm above from the top of YP250: a) linear at the peak field ($z = 3$ mm in Fig. 5); b) optimized at the YP250 geometric center ($z = 0$ mm in Fig. 5). All units are in mT.

Fig. 7. Normalized temporal decays of the trapped fields in Fig. 5; red triangles: Linear; b) black squares: Optimized.

(a)

(b)

Fig. 8.
Pictures of: (a) YP750 and (b) YPB750.

Fig. 9.

Trapped field plots along the magnet axis; black open squares: 0.75 T test with YP750; black open circles: 0.25 T YP750; blue solid triangles: 0.75 T YPB750; blue solid diamonds: 0.25 T YPB750.

Fig. 10.

Temporal decay plots of peak trapped field; black open square: 0.75 T test with YP750; black open circle: 0.25 T YP750; blue solid triangle: 0.75 T YPB750; blue solid diamond: 0.25 T YPB750.

Fig. 11. Radial field mappings of: (a) 0.75 T YP750 at peak field ($z = 3$ mm); (b) 0.25 T YP750 ($z = 0$ mm); (c) 0.75 T YPB750 ($z = -2$ mm); (d) 0.25 T YPB750 ($z = 0$ mm). All units are in mT.

Table I

Measured Trapped Fields With and Without a Center Hole

Bz @ center	#216	#244	#382	Cal. [6]
without a hole (before) [mT]	22	25	27	25
with a hole (after) [mT]	5.5	5.0	6.5	5.0

Table II

Peak Trapped Fields [MT] For Different Stack

Module #	Orthogonal square		Polygon star	
	1 st	2 nd	1 st	2 nd
Module #1	46.7	47.0	44.8	45.0
Module #2	47.8	48.0	47.6	47.8
Module #3	46.7	46.8	44.6	44.7

Table III

Axial and Radial Field Errors of the 0.25 T Tests in Figs. 10 and 11 Orientations

	e_z^* [ppm]	$Z1$ [ppm/mm]	$Z2$ [ppm/mm ²]	$Z3$ [ppm/mm ³]	$Z4$ [ppm/mm ⁴]	$e_R^†$ [ppm]
YP750	471	-51.5	-139	-1.18	-0.0970	110
YPB750	520	-104	-132	-1.35	0.0721	74