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A Stack of YBCO Annuli, Thin Plate and Bulk, for Micro-NMR Spectroscopy

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Abstract

A new annulus magnet, the latest in a series of compact magnets being developed for NMR spectroscopy applications at the MIT Francis Bitter Magnet Laboratory, was built and tested in a bath of liquid nitrogen at 77 K. The magnet, YP2800, a stack of 2800 thin YBCO *plate* annuli, each either 40 - or 46-mm square and 0.08-mm thick with a 26-mm bore, is an upgraded version of the two earlier plate annulus magnets, YP750 (750 plates) and YP1070 (1070). This paper presents construction details and test results of YP2800. Its spatial field homogeneity and temporal stability were measured, analyzed, and compared with those of YP750 and YP1070. Also, four YBCO bulk

annuli, each 26-mm i.d., 46-mm o.d., and 5.2-mm thick, were added to YP2800 and their impacts on field strength and homogeneity were investigated experimentally.

Keywords

Compact annulus magnet; Micro-NMR spectroscopy; YBCO Bulk annuli; YBCO thin plate annuli

I. INTRODUCTION

AS applications of NMR spectroscopy rapidly expand, the need for NMR magnets with a variety of options to users is growing. In applications where an NMR sample volume can be less than 10 micro-liters, known as micro-NMR spectroscopy, a “conventional” magnet of a 54-mm room-temperature (RT) bore with liquid-helium (LHe) cooling may not be the best option, economic, technical, logistic [1–3]. Thus today, compact (RT bore < 54 mm), LHe-free NMR magnets, based primarily or solely on HTS, are being developed [4]–[11].

Since 2009, we have been engaged in a 2-phase program of which the specific aim is to complete a compact 300-MHz/38-mm magnet for micro-NMR spectroscopy. In Phase 1, currently ongoing, a 150-MHz/9-mm annulus magnet will be built [4]. Key design concepts of the annulus magnet include: 1) an annulus magnet assembled from a stack of YBCO annuli, thin (80- μ m thick) plate and/or bulk (5-mm thick) [5]–[8]; 2) the field-cooling (FC) technique to *trap* a magnetic field in the annulus magnet, inserted in the bore of a background magnet [5], [12]; and 3) solid nitrogen to increase the system thermal mass in the operating range 10 – 15 K [5], [12].

Since the first pilot magnet, YP500, an assembly of 500 YBCO plate annuli, was built in 2009 [6], we have built two upgrades, YP750 (750 plates) and YP1070 (1070), both operated at 77 K and 4.2 K, of which the test results have been reported [7], [8]. This paper focuses on our latest upgrade, YP2800, an assembly of 2800 thin YBCO plate annuli and its variant, in which four bulk annuli are added to YP2800. Primary results, experimental and analytical, of YP2800 and its variant, both tested at 77 K, include field strength, spatial field homogeneity, and temporal stability as well as comparison with those of YP750 and YP1070.

II. CONSTRUCTION OF YP2800

A five-step stacking procedure of a thin-plate annulus magnet is as follows. First, 40- and 46-mm square plates are prepared from wide YBCO tapes originally manufactured by American Superconductor Corp. (AMSC) as their standard product. Second, a 26-mm center hole is laser-cut in each plate. Third, the plates are grouped as *5-plate modules*. Fourth, each 5-plate module is field-cooled in a LN₂ container with a permanent magnet [7], trapping a field. Finally, the 5-plate modules are stacked in a way that the module with the largest trapped field at the center and the other modules in descending order of their trapped fields towards the two ends of the stack.

Fig. 1 shows pictures of YP750, YP1070, and YP2800 annulus magnets, the key parameters of which are listed in Table 1. The heights of YP750, YP1070, and YP2800 are 60 mm, 86 mm, and 224 mm, respectively. The peak trapped field at the center of YP2800 at 77 K is ~ 1.5 times larger than those of the other annulus magnets, chiefly owing to the presence of more modules of greater trapped fields. Fig. 2 shows plots of measured axial module field vs. magnet axis (from the center, 0, in both directions) in the optimized stack of: 214 modules in YP1070 (blue circles); and 560 modules in YP2800 (black squares). Because YP750 is comprised of 25-plate modules, its plot is not included in Fig. 2.

III. TEST RESULTS AND ANALYSES

A. Test Procedure

The test procedure for an annulus magnet is as follows. First, a magnet, housed in a “Styrofoam cryostat,” is placed in the 300-mm RT bore of a 5-T background magnet [7]. Second, the background magnet is charged to a target field with the magnet still at room temperature, after which LN_2 is supplied into the cryostat to turn the magnet superconducting. Finally, after a period of 20 minutes, long enough to cool the entire annulus magnet to 77 K, the background magnet is discharged at a rate of -1 A/min. Once the field cooling (FC) process is done, the trapped field of the annulus magnet is measured with a 3-D field mapper having an effective sensing area of $0.05 \text{ mm} \times 0.05 \text{ mm}$ with a spatial resolution of $10 \mu\text{m}$ [6]. Separately, a temporal field decay is measured for the first 1–2 hours, followed by axial and X- Y field scans along the magnet center and on the magnet center plane, $z=0$, respectively.

Each magnet was tested twice with different background fields strengths. In the first test, named PEAK, an FC field much larger than an expected peak trapped field was applied. In the second test, named LOW, 70 % of the peak trapped field obtained in PEAK became an FC field, primarily to improve the field homogeneity of the annulus magnet. Here, we present the results of PEAK and LOW tests performed on YP2800 and compared them with those of YP750 and YP1070 [7], [8].

B. Axial Field Homogeneity

Fig. 3 presents axial field vs. axial location plots of YP2800 (squares), YP1070 (circles), and YP750 (triangles). Solid and open symbols are for PEAK and LOW, respectively. The numbers in the parentheses in the inset are FC fields. In general, field homogeneity improves, as is expected, with magnet height (length) and deteriorates with FC field. For better comparison, axial field plots, each normalized to its peak field, are presented in Fig. 4. Table 2 gives a summary of their axial field gradients and overall field errors, defined as a peak-to-peak field difference within a $|z| < 2 \text{ mm}$ space divided by the center field. The best field homogeneity, 186 ppm, was obtained from the YP2800 LOW test. Note that the difference of field errors in YP2800 between PEAK and LOW is only 25 ppm, while those in YP750 and YP1070 are 638 and 4341 ppm, respectively. These results imply that a longer annulus magnet, as expected, can trap a more homogeneous field than a shorter one and may alleviate homogeneity requirement of the FC field.

C. Radial Field Homogeneity

Fig. 5 presents four sets of 2-D (X-Y) trapped field contours of YP750, YP1070 and YP2800, scanned at the midplane ($z = 0$) with a 3-D field mapper over a $6 \text{ mm} \times 6 \text{ mm}$ area about the magnet axis. The three numbers in the parentheses of each set are respectively for magnet, FC field, and overall radial field error defined as a peak-to-peak field difference within a $|r| < 1 \text{ mm}$ radial space divided by the center field. In general, radial homogeneity improves with magnet length and worsens with FC field. YP2800 has the best radial homogeneity, though its field contours look less concentric because higher order radial field errors become more dominant as the overall homogeneity is improved. Note that in YP2800 the radial homogeneity difference between PEAK and LOW is only 2 ppm while those of YP750 and YP1070 are 972 and 303 ppm, respectively.

D. Temporal Stability

Fig. 6 presents normalized axial field vs. elapsed time plots for YP2800 (squares), YP1070 (circles), and YP750 (triangles). Each field is normalized to the field at $t = 0$, the start of measurement, which began 30 minutes after completion of the FC process. During an elapsed period of ~ 2 -hours, the trapped fields of PEAK (solid data) dropped by 4–9 %, while those of LOW (open data) by 0.01 – 0.04 %. The temporal decay rate of YP2800 in LOW, determined at $t = 90 \text{ min}$ in Fig. 6, is 120 ppm/hr, which is similar to those of YP750 (80 ppm/hr) and YP1070 (111 ppm/hr).

E. YP2800 with YBCO Bulk Annuli

Four bulk annuli of nearly identical i.d., o.d., thickness, and trapped field capacity were combined with YP2800. Table 3 compares key parameters of the bulk annulus and the plate annulus, whose pictures are presented in Fig. 7 (a). A trapped field of a plate annulus, 5 mT, is much smaller than that of a bulk annulus, 208 mT, both measured at the center. Figs. 7 (b) and (c) present respective X-Y field contours scanned at 1 mm above the top surface of the bulk annulus and a new 65-plate stack, whose thickness approximates that of the bulk annulus. The bulk center field, 178 mT, is 30 % larger than that of the 65-plate stack, 124 mT, which implies that a bulk can trap a greater field than a stack of plates with the same length. Because a bulk is much thicker than a single plate, greater screening currents [13], [14] flow in an assembly of bulk annuli than those in an assembly of thin plate annuli: a bulk annulus magnet will generate a greater trapped field but of an inferior field quality, presenting a greater challenge in field shimming.

To investigate the effect of bulk annuli on trapped field performance of YP2800, four bulk annuli were added: 1) all four at the center of YP2800; or 2) two pairs about the center separated axially by 150 mm. In either test, an FC field of 0.46 T was applied. Fig. 8 shows axial field vs. axial distance plots of 4-bulk-at-center-YP2800 (triangles), 2-bulk-apart-YP2800 (circle), and, for comparison, plain YP2800. When the bulks were at the center, the center field strength was improved by $\sim 7 \%$ but field homogeneity was significantly degraded. When the bulk pairs were apart, they had no beneficial effect on the center field but negative effects on the field quality.

IV. CONCLUSION

As a part of Phase 1 project of a two-phase program to complete a 300-MHz/38-mm micro-spectroscopy NMR magnet at the conclusion of Phase 2, we have been building and testing a series of compact annulus magnets. The latest in the series is an annulus magnet, YP2800, assembled from a stack of 2800 thin plate YBCO annuli, both 40-mm and 46-mm squares, each 0.08-mm thick and a ϕ 26-mm bore. YP2800 was tested in a bath of liquid nitrogen at 77 K. Its spatial field homogeneity and temporal stability were measured, analyzed, and compared with those of the two earlier magnets, YP750 (750 plates) and the YP1070 (1070 plates). YP2800 produced the best axial and radial field homogeneities of 186 ppm within $|z| < 2$ mm and 80 ppm within $|r| < 1$ mm of the magnet center. The three annulus magnets had similar temporal stabilities in the range 80 – 110 ppm/hr. Generally, the greater the annulus magnet length the higher is a trapped field and of superior field quality. Although we believe that a combination of bulk and plate annuli is the veritable way to achieve a field strength > 10 T (> 425 MHz) with a compact annulus magnet, our experiment with one example of such a magnet, 4-bulk-YP2800, has shown that improvement in field strength comes with degradation in field quality. The combined bulk-plate annulus magnet configuration clearly requires further study.

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Fig. 1.
Pictures of YP750, YP1070, and YP2800.

Fig. 2.
Axial center field vs. axial distance of: 214 modules in YP1070 (circles); and 560 modules in the YP2800 (squares)

Fig. 3. Axial field vs. axis location plots of YP2800, YP1070, and YP750 from PEAK (solid data) and LOW (open data) tests.

Fig. 4.

Normalized axial field vs. axial location plots of YP2800, YP1070, and YP750 from PEAK (solid data) and LOW (open data) tests.

Fig. 5. X-Y scans of axial trapped fields at midplane of YP750 (top two), YP1070 (middle two), and YP2800 (bottom two). Field values are in mT.

Fig. 6. Normalize axial field vs. elapsed time plots for YP2800 (squares), YP1070 (circles), and YP750 (triangles). For each annulus magnet, solid data are for PEAK and open data are for LOW.

Fig. 7.

(a) Picture of a YBCO plate and a bulk; axial field contours measured at 1 mm above top surface of (b) 65-plate stack and (c) single bulk.

Fig. 8.

Axial field vs. axial distance plots for 4 bulks at center in YP2800 (triangles), 2 bulks apart in YP2800, (circles) and plain YP2800 (squares).

TABLE 1

Key parameters of YP750, YP1070, and YP2800

Parameters	YP750	YP1070	YP2800
40-mm; 46-mm plates	750; N/A	750; 320	850; 1950
Modules ; plates per module	30; 25	214; 5	560; 5
Stack height (magnet length) [mm]	60	86	224
Peak center field, B_z at 77 K [T]	0.43	0.45	0.64

TABLE 2

Axial Field Gradients and Overall Field Error

Test	Z1 [ppm/mm]	Z2 [ppm/mm ²]	Z3 [ppm/mm ³]	Z4 [ppm/mm ⁴]	Overall [*] [ppm]
YP2800 (2.0T)	-6.04	-51.3	0.813	-0.0132	211
YP2800 (0.46T)	-56.1	-17.9	-0.245	-5.79e-4	186
YP1070 (1.0 T)	471	-525	-0.193	0.214	1156
YP1070 (0.3 T)	-112	-74.8	0.697	-0.0367	518
YP750 (1.0 T)	-1010	-712	-1.03	0.182	4873
YP750 (0.3 T)	-58.5	-102	-0.433	-0.285	532

^{*} Measured within an axial space of $|z| < 2$ mm

TABLE 3

Key Parameters of Bulk and Thin Plate

Parameters	Bulk	Plate
i.d.; o.d. or square width [mm]	26; 47	26; 46
Thickness [mm]	5.2	0.08
Trapped field at the center [mT]	208	5

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