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Bulk and Plate Annulus Stacks for Compact NMR Magnets: Trapped Field Characteristics and Active Shimming Performance

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Abstract

We have constructed two “annulus” magnets, YP2800 and YB10; each consists of 2800 YBCO thin square “plate annuli” (YP2800) and 10 YBCO thick “bulk annuli” (YB10). Their trapped field characteristics, spatial and temporal, were investigated and compared, experimentally and analytically. Two sets of field-cooling tests were performed at 77 K: (1) maximum trapped field tests, where a 2-T background field was applied to investigate the maximum trapped field capability of the two magnets; and (2) reduced trapped field tests, where spatial homogeneity improvement of the two magnets was investigated after field cooling with a reduced background field. Also, a Z1 copper shim coil was designed, constructed, and operated, alone and with YP2800 and YB10. When it was operated with the annulus magnets at 77 K, a significant attenuation of the shim coil strength was observed due to the screening currents induced within the annulus magnets.

Keywords

Active shimming; annulus magnet; field cooling; magnetization; screening current; trapped field

I. INTRODUCTION

SINCE 2009, we have been developing compact “annulus” magnets that consist of a stack of YBCO annuli [1]–[4] for micro-NMR spectroscopy applications [5]–[7]. An annulus magnet can “trap” a magnetic field by the “field cooling” procedure [8] and requires no joints between HTS (high temperature superconductor) annuli. Therefore, it requires no current leads and operates intrinsically in a persistent mode. In consequence, the whole magnet system including the cryogenic part can be highly simplified and compact.

We have used two types of annuli, “thin plates” and “thick bulks”, either in one type exclusively or in combination. In this research, 10 YBCO bulk annuli are used for an all-bulk stack (YB10) while 2800 YBCO thin “square” annuli for an all-plate stack (YP2800). Trapped field tests of YP2800 and YB10 were performed in a bath of liquid nitrogen (LN_2) at 77 K and their trapped field characteristics, spatial homogeneity and temporal stability, were investigated, experimentally and analytically. Also, a Z_1 shim coil wound with copper wires was constructed and operated, alone and with YP2800 and YB10 to investigate the performance of the Z_1 shim coil in operation with annulus magnets.

II. EXPERIMENTAL SETUP AND ANALYTIC MODEL

A. Construction of YP2800 and YB10

Fig. 1 shows pictures of YP2800 and YB10, of which key parameters are listed in Table I. The YP2800 consists of a total of 2800 plates, each either 40-mm or 46-mm square with a 26-mm hole machined at the center. The plates, originally the AMSC’s 2 G wide conductor [9], [10], were cut to form a square shape. During construction, a group of 5 plates was assembled to a single module and the trapped field strengths of 560 modules were measured individually in a bath of liquid nitrogen (LN_2) at 77 K. Then, the modules were stacked in a way to obtain the best spatial field homogeneity. The test results of all modules and the stacking method have been described in [4].

The YB10 consists of 10 bulk annuli of which i.d., o.d., and thickness values are listed in Table II. Each annulus was field-cooled individually in a bath of LN_2 at 77 K; the center trapped field (B_{z0}) and the field homogeneities within a $|r| < 1$ mm space of each annulus were measured and presented in Table II. To achieve the best field homogeneity and largest trapped field strength, we placed the largest trapped-field bulk at the midplane, with the remaining bulks in the decreasing order of trapped-field strengths toward both ends of a 10-annulus stack (Table II).

B. Trapped Field Test Setup and Procedure

For a field cooling, a 5-T 300-mm RT (room-temperature) bore background magnet was used to provide an external field. The annulus magnet, YP2800 or YB10, in an LN_2

container was placed at the center of the background magnet. After the background magnet was fully energized to a target field, the LN₂ was supplied to cool down annulus magnet to 77 K. Once the magnet was fully cooled and superconducting, the background magnet was discharged at a rate of 1 mT/s. After the background magnet was completely discharged, an axial distribution of the trapped fields along the annulus magnet center was measured, three times, using a search coil, 5 min, 30 min, and 60 min after the moment that the background magnet had been completely discharged. Fig. 2 presents an axial field profile from the LTS background magnet at an operating current of 16.7 A (1 T). The axial field uniformity over a space for YB10 (53 mm) and YP2800 (224 mm) is 3% and 16%, respectively.

Two sets of tests were performed: 1) maximum field test (MFT) with a 2-T field cooling to investigate a maximum trapped field capability of YP2800 and YB10; and 2) reduced field test (RFT), where a 70% of the maximum trapped field was applied by the background magnet to improve the spatial field homogeneity from that of MFT, though sacrificing trapped field strength.

III. TRAPPED FIELD TEST RESULTS

A. Maximum Field Test

Figs. 3 and 4 show the axial field distributions of YP2800 and YB10, respectively, from MFT. Open squares, circles, and triangles stand for the trapped fields measured at 5, 30, and 60 minutes, respectively. From the measured trapped field at the center (B_{zo}), an “average” overall current density, J_{ea} , can be calculated by (1), where r_1 , α , and β are, respectively, magnet inner radius, ratio of magnet outer radius to r_1 , and ratio of magnet height to r_1 [8]. For simplicity, each “square annulus” of YP2800 was modeled as a regular annulus with an outer diameter of 52 mm to make the same “effective” surface area with that of the 46-mm square annulus. Table III presents the measured B_{zo} and the calculated J_{ea} of YP2800 and YB10 from MFT and RFT. Although the B_{zo} of YP2800 is similar to that of YB10, the J_{ea} of YB10 is 20% larger than that of YP2800

$$J_{ea} = \frac{B_{zo}}{r_1 \beta \{ \ln(\alpha + \sqrt{\alpha^2 + \beta^2}) - \ln(\alpha + \sqrt{1 + \beta^2}) \}}. \quad (1)$$

Once J_{ea} was obtained, the axial center field distributions of YP2800 and YB10 were calculated by use of the elliptic integral [11], and presented in Figs. 3 and 4 as dashed lines with diamonds. Note that calculation assumes an average current density (J_{ea}) uniformly distributed over the entire YP2800 and YB10. The calculated fields in Figs. 3 and 4 are much “broader” than the measured ones, which indicates a non-uniform current distribution within each annulus magnet, due chiefly to the lower critical currents of the plates and bulks placed near the top and bottom ends of the stacks.

Fig. 5 presents B_{zo} vs. time plots of YP2800 (squares) and YB10 (circles) from MFT. A linear decay of B_{zo} in the log time axes demonstrates that the field decay in YP2800 and YB10 originates mostly from flux flow or creep in HTS [8], [12]–[15]. Note that, although J_{ea} of YB10 is larger than that of YP2800 in Table III, the decay rate of YB10 is greater than

that of YP2800 for the same initial trapped field of 0.67 T. This implies that a longer annulus magnet is more preferable than a shorter one not only for spatial homogeneity but also for temporal stability.

B. Reduced Field Test for Homogeneity Improvement

In RFT, the test configuration was not changed from MFT except the reduced background field from 2 T to 0.46 T (70% of the peak trapped field, 0.67 T) for field cooling. Figs. 3 and 4 also present the axial field distributions of YP2800 and YB10, respectively, from RFT; Solid squares, circles, and triangles stand for the trapped fields measured at 5, 30, and 60 minutes, respectively, after the background magnet was completely discharged. The peak trapped fields of YP2800 and YB10 at 5 min are 0.44 T and 0.45 T, respectively, which are close to the field-cooling field of 0.46 T as expected. The field distributions about the magnet center from RFT are more homogeneous than those from MFT in both YP2800 and YB10, though the improvement was more pronounced in YP2800. Note that the axial field homogeneity of YP2800 in $|z| < 25$ mm from RFT is 0.8% while that from the background magnet in Fig. 2 is 3%. This implies that the trapped field homogeneity of an annulus magnet can be further improved from that of the initial background field if an annulus magnet is “long.” The temporal decays of YP2800 and YB10 were negligible in RFT.

IV. ACTIVE SHIMMING

A. Construction of Z1 Shim Coil and Test Setup

Fig. 6 shows the Z1 shim coil; its key parameters are summarized in Table IV. The basic configuration is the anti-Helmholtz coil [10] wound with AWG20 copper wires. The calculated Z1 gradient at the coil center is 0.74 mT/cm/A. YP2800 or YB10 can be installed in the cold bore of the shim coil and the total assembly was placed in a bath of LN₂ for tests at 77 K. In each test, axial fields along the magnet center were measured with a Hall sensor of a 97.9-mV/T sensitivity. A 3-D plotter [2]–[4] was used to accurately control the position of the Hall sensor. Since the field strength from the shim coil was weak (< 1 mT), a nanovoltmeter, after careful cancellation of the offset from the earth field and noise, was used to measure the Hall sensor voltages.

B. Test Procedure and Results

Fig. 7 summarizes operation results of the Z1 shim. Firstly, it was operated alone at +1 A (solid squares) and –1 A (open squares) at RT to confirm its designed field performance without any annulus magnets. Secondly, it was operated, at the same currents, with YP2800 at RT (triangles); the fields were attenuated due to the magnetic substrates of the square-plate annuli YP2800. From a finite element analysis, the average magnetic permeability (μ_r) of the substrates was estimated as 4 for YP2800 to have a similar attenuation of fields to the measured one in Fig. 7. Thirdly, the Z1 shim coil was operated, again at the same current of ± 1 A, with YP2800 at 77 K (red circles) and almost no field (< 0.1 Gauss) was detected along the magnet center due to the screening currents induced within the annuli of YP2800. The final operation of the Z1 shim coil with YB10 at 77 K (magenta diamonds) and ± 1 A, confirmed that the screening-current effect of annulus magnets significantly attenuate a shim field. Note that YB10 is 53 mm high, while the screening effect was limited to a $|z| < 20$ mm

along the z-axis. The results prove that, when a shim coil is operated with an annulus magnet, its strength will be significantly attenuated. Currently, we are testing NbTi shim coils to further investigate this issue at 4.2 K.

V. CONCLUSION

Two annulus magnets were constructed, YP2800 and YB10; YP 2800 consists of 2800 “square plate” annuli while YB10 of 10 YBCO bulk annuli. Trapped field characteristics, spatial and temporal, of YP2800 and YB10 were investigated and compared, experimentally and analytically. Two sets of tests were performed: 1) maximum field tests (MFT), where a 2-T background field was applied to investigate the maximum trapped field capability of YP2800 and YB10; and 2) reduced field tests (RFT), where spatial homogeneity improvement of the two annulus magnets was investigated after field cooling with a reduced background field. The field homogeneity of YP2800 near the magnet center, $|Z| < 25$ mm was 0.8% better than that of the background magnet field of 3%, which demonstrates that the trapped field homogeneity of an annulus magnet can be further improved from that of the initial external field with a longer annulus magnet. YP2800 was better than YB10, not only in spatial homogeneity but also in temporal stability though the average overall current density of YB10 was measured higher than that of YP2800. This implies that a “long” annulus magnet will have a superior performance in both temporal stability and spatial homogeneity. The Z1 shim coil tests have shown a significant attenuation of the shim coil strength when it was placed outside YP2800 (and YB10), chiefly owing to the screening currents in the annulus magnets.

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Fig. 1.
Pictures of YP2800 and YB10.

Fig. 2.

Axial field profile from the background magnet at an operating current of 16.7 A, which corresponds to a center field of 1 T. The field uniformity over a space for YB10 and YP2800 are 3% and 16%, respectively.

Fig. 3.

Axial field distribution along the center of YP2800 from MFT (open symbols) and RFT (solid symbols).

Fig. 4.

Axial field distribution along the center of YB10 from MFT (open symbols) and RFT (solid symbols).

Fig. 5.
Field decay of YP2800 (squares) and YB10 (circles) from MFT.

Fig. 6.
Picture of the Z1 shim coil. YP2800 or YB10 can be installed within the shim cold bore.

Fig. 7.
Summary of Z1 shim test results.

TABLE I

SPECIFICATIONS OF YP2800 AND YB10

Parameters		YP2800	YB10
Material		YBCO	YBCO
Size of plate or bulk	[mm]	40 or 46 square	$\phi 47$
Thickness	[mm]	0.08	5.2
Center hole	[mm]	26	26
Magnet			
Total plates or bulks		2800	10
Overall height	[mm]	224	53
Peak trapped field, B_{zp} at 77 K	[T]	0.67	0.67

TABLE II

SPECIFICATION OF 10 BULKS TRAPPED FIELD TEST RESULTS AT 77 K

ID	i.d. [mm]	o.d. [mm]	height [mm]	B_{z0} [mT]	Homogeneity ($ r < 1$ mm) [%]
B1	25.1	46.6	5.0	40	0.94
B2	25.3	46.8	5.3	118	0.24
B3	25.3	47.2	5.3	132	0.26
B4	25.8	46.5	5.2	160	0.23
B5	25.6	46.5	5.5	220	0.24
B6	26.5	45.4	5.1	171	0.27
B7	26.1	45.8	5.4	153	0.28
B8	26.3	46.8	5.0	124	0.31
B9	25.3	47.0	5.3	36	2.7
B10	26.0	46.9	5.4	6.2	0.29
Avg.	25.7	46.6	5.3	116	--

TABLE III

MEASURED CENTER FIELDS AND CALCULATED OVERALL CURRENT DENSITIES OF YP2800 AND YB10 FROM MFT AND RFT

Parameters		MFT		RFT	
		YP2800	YB10	YP2800	YB10
B_{zo}	[T]	0.67	0.67	0.44	0.45
J_{ca}	[A/mm ²]	41.6	49.3	27.3	33.1

TABLE IV

SPECIFICATIONS OF Z1 COPPER SHIM COIL

Parameters		Values
Wire		Cu, AWG20
$r_1; r_2$	[cm]	4.6; 5.3
$z_1; z_2$ (upper coil)	[cm]	1.5; 3.5
Total turns per coil		172
J_c at 1 A	[A/cm ²]	121.2
Z1	[mT/cm/A]	0.74