Trapped Field Characteristics of Stacked YBCO Thin Plates for Compact NMR Magnets: Spatial Field Distribution and Temporal Stability

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Abstract—This paper presents experimental and analytical results of trapped field characteristics of a stack of square YBCO thin film plates for compact NMR magnets. Each YBCO plate, 40 mm × 40 mm × 0.08 mm, has a 25-mm diameter hole at its center. A total of 500 stacked plates were used to build a 40-mm long magnet. Its trapped field, in a bath of liquid nitrogen, was measured for spatial field distribution and temporal stability. Comparison of measured and analytical results is presented: the effects on trapped field characteristics of the unsaturated nickel substrate and the non-uniform current distribution in the YBCO plate are discussed.

Index Terms—Compact NMR, spatial homogeneity, temporal stability, trapped field, YBCO plate.

I. INTRODUCTION

A superconducting magnet occupies the largest space in most nuclear magnetic resonance (NMR) spectrometers. For most applications an NMR spectrometer requiring a small footprint is desirable, which is feasible with a “compact” NMR magnet. We proposed a compact NMR magnet comprising a stack of high temperature superconductor (HTS) annuli in which its trapped field is induced by field cooling [1], [2]. Our 2-phase program to develop a compact annulus NMR magnet began this year, with an ultimate target to complete a 500 MHz compact NMR magnet.

This paper presents preliminary results, experimental and analytical, of field-cooled trapped-field characteristics of a stack of square YBCO thin plates. Each square YBCO plate, 40 mm × 40 mm × 0.08 mm, has a 25-mm diameter laser-cut hole at its center. A magnet, 40 mm long, contains a total of 500 stacked plates in a serrated way in order to minimize radial harmonic field errors from non-circular current loops in the final assembly. Its trapped field, in a bath of liquid nitrogen at atmospheric pressure, was measured for spatial distribution and temporal stability by a Hall sensor with a 3-D automatic plotter. A 5-T cryocooled low temperature superconductor (LTS) magnet of which room-temperature (RT) bore was 300 mm provided a background field up to the 3 T during the tests. Comparison of measured and analytical results is presented: The effects of unsaturated nickel substrates as well as non-uniform current distributions in YBCO thin plates on trapped field characteristics are discussed.

II. SYSTEM CONFIGURATION

A. YBCO Thin Plate

Fig. 1 presents (a) a picture and (b) a schematic drawing, with dimensions, of a sample YBCO thin plate. All 500 YBCO plates were supplied by American Superconductor Corporation (AMSC). Parameters of the YBCO plate are summarized in Table I. The thickness of nickel substrate is 75 micron, which is about 94% of the entire plate. By reducing the substrate thickness, the overall current density can be improved.

B. Assembly of 500 YBCO Plates

A total number of 500 YBCO plates are stacked to build a test magnet, called “YP500,” as seen in Fig. 2. Since each plate is rectangular, a 16-serrated guide structure with 22.5° angular displacement between each tooth was used to minimize tesseral field errors from non-circular current loops in the final assembly. Fig. 2 presents (a) a picture taken during the stacking process using the serrated guide structure and (b) the completed assembly of 500-plate YBCO stack with a support structure. Table II summarizes magnet parameters of the YP500.
TABLE I
PARAMETERS OF THE YBCO THIN PLATE

| Parameter                  | Value               |
|----------------------------|---------------------|
| Material                   | YBCO                |
| Manufacturer               | AMSC                |
| Width x Length             | [mm] 40 x 40        |
| Center hole i.d.           | [mm] 25             |
| Overall thickness          | [µm] 80             |
| YBCO layer thickness       | [µm] 0.8            |
| Nickel substrate thickness | [µm] 75             |
| \( J_c \) of YBCO @ 77 K, 0.2 T | [MA/cm²] 0.2 – 0.6 |
| \( J_c \) of YBCO @ 77 K, 0.2 T | [ka/cm²] 2.0 – 6.0 |

C. Background Magnet and Field Measurement System

During field cooling, a separate cryostat housing the YP500 and filled with liquid nitrogen was placed in a 300-mm room temperature (RT) bore of a cryocooled 5-T low temperature superconductor (LTS) magnet. Fig. 3 shows a to-scale drawing of the LTS magnet and the YP500; overall i.d., o.d., and height of the LTS coils are 327, 415, and 338 mm, respectively, and its operating current to reach the 5-T center field is 84 A. Spatial homogeneity of the LTS magnet within 6 cm DSV (diameter spherical volume) where the YP500 is placed is 1.2%. Once the field cooling process is completed, the field-cooled YP500 together with the cryostat was transported to a field mapping site where an automatic 3-D plotter, in Fig. 4, was located. A Hall sensor with an effective sensing area of \( 0.05 \times 0.05 \) mm² was attached to the bottom of a vertical stage of the mapper. Spatial resolution of each mapping is 0.2 mm.

TABLE II
MAGNET PARAMETERS OF THE 500-STACKED YBCO PLATES

| Parameter                  | Value               |
|----------------------------|---------------------|
| Vital Statistics           |                     |
| Number of YBCO plates      | 500                 |
| Overall i.d.; o.d.         | [mm] 25; 56.6       |
| Overall height             | [mm] 40             |
| Operation                  |                     |
| Peak trapped field @ 77 K (typical) | [T] 0.18        |
| Peak trapped field @ 4.2 K (typical) | [T] 2.3          |

III. FIELD MEASUREMENT

The field cooling process consists of the following five sequential steps: (1) place the YP500 with its own cryostat, in the RT bore of the 5-T LTS magnet; (2) energize the LTS magnet to reach a target external field; (3) pour liquid nitrogen to the YP500 cryostat; (4) after the YP500 cools down completely to 77 K, slowly de-energize the LTS magnet; and (5) transfer the field-cooled YP500 to the field mapping site and measure the trapped field. The current ramping down rate of the LTS magnet during step 4 was set to 1 A/min, which corresponds to 595 gauss/min at the center of YP500.

A. One Plate Measurement

Before the 500 YBCO plates were assembled, the trapped field distribution of a sample plate was measured. Fig. 5(a) presents a field mapping of the top surface of the sample plate; a peak field of 0.0221 T was trapped from an external field of 0.1 T at the end of the field cooling process. Figs. 5(b) and 5(c) are corresponding trapped field and current distributions calculated by a nonlinear two-dimensional finite element method with iteration [3], [4]. For simplicity in calculation, the Bean critical state model was applied with the assumption of a constant critical engineering current density of \( 1.90 \times 10^3 \) A/cm² over the entire cross-section of a 80-µm thick YBCO plate. As seen in both measured and calculated results, the peak fields occur at the four corner edges of the YBCO plate near the hole, because the azimuthal current distributions in the plate are not circular. Owing to the \( J_c \) distribution that is non uniform and
Fig. 5. (a) Axial field measurement on the top surface of a sample YBCO plate, (b) calculated axial field distribution, and (c) calculated current distribution. The numbers in each legend indicate trapped field with a unit of gauss.

anisotropic, the measured field distribution is not as symmetric as the calculated one. Note that the calculation assumes a relative permeability of the 75 μm Nickel substrate as 2 according to an extrapolation of Nickel permeability measurements in [5] and [6] in order to roughly consider its effect on trapped field distribution. In a trapped field of the real NMR system, 2.35 T, the Nickel substrates will be fully saturated. However, its impact on NMR-grade field homogeneity needs to be investigated in further detail and it will be reported separately.

B. Axial Field Distribution of the 500-Plate YBCO Magnet

Axial field distributions, measured along the YP500 axis at two hours after field cooling was completed, are presented in Fig. 6. Three different external fields were applied during three field cooling processes—0.1 T, 0.25 T, and 3.0 T. The positive displacement in the x axis of Fig. 6 indicates that YBCO plates located above the YP500 center in Fig. 3 were made from better performing material. As seen in Fig. 6, the peak trapped field from the 0.25 T external field is 0.187 T, only 2% larger than that from the 3.0 T, which indicates that the trapped field in the YP500 becomes fully saturated for an external field larger than 0.25 T. In comparison, a peak of 0.0757 T was measured from the 0.1 T external field. In this case, although the trapped field is only 40% of the maximum field trapping capability of the YP500, the center trapped field is only 76% of the applied field, 0.1 T, because of the unsaturated Nickel substrate. The overall field homogeneities of the 0.1, 0.25, and 3.0 T cases are 7.7, 44, and 45%, respectively, in 40 mm axial length. Note that the overall field homogeneity was improved from 44% to 7% as each YBCO plate current became unsaturated and each plate in the assembly can conserve more evenly the original flux from the external LTS magnet of which field distribution is relatively homogeneous.

According to the “saturated” trapped field results, red triangles and blue circles in the Fig. 6, it is obvious that the critical current density of each plate is not uniform. Each plate’s critical current density was estimated by the Inverse Problem technique with Evolution Strategy [7]. Here, (1) is used as objective function to be minimized, where $J_i^c$, $B_i^e$, and $B_i^m$ are, respectively, the i-th plate critical current density, calculated trapped fields, and measured. With estimated critical current densities, the calculated field, green line in Fig. 6, agrees well with the measured one with an assumption that currents in all the plates were fully saturated.

\[
\int_{DSV} f_{ij}(J_i^c) = \int \left( B_i^e(z) - B_i^m(z) \right)^2 dz, \quad 1 \leq i \leq 500 \quad (1)
\]

Fig. 7 presents a comparison between the “unsaturated” trapped field, enlarged from the black square in Fig. 6, and the estimated critical current densities of the 500 YBCO plates. Note that the two graphs have a similar pattern of axial distribution. This implies that, even in an unsaturated condition, non-uniform distribution of each plate’s individual critical current density still affects the final spatial field homogeneity. So, an optimized sequence of stacking order is required to further improve field homogeneity in a stacked YBCO-plate magnet.

C. Temporal Stability of the 500-Plate YBCO Magnet

To investigate temporal stability of the trapped fields, three field decay graphs, measured for over an hour, of the 0.1, 0.25,
and 3.0 T cases are presented in Fig. 8; the time scale of each graph was linearly adjusted for easy comparison. According to Fig. 8, temporal stabilities of 0.1, 0.25, and 3.0 T are 0.033, 4.1, and 6.3% per hour in average, respectively. As the trapped field becomes smaller, the temporal stability improves as expected. Note that the amount of the trapped field from the 0.1 T external field; Red squares: 0.25 T; Blue circles: 3.00 T. Time scale is adjusted for ease of comparison.

Fig. 7. Black squares: “unsaturated” axial trapped field measured along the YP500 axis after the field cooling of 0.1 T (enlarged view of the black square in Fig. 6). Blue circles: engineering current density of each YBCO plate estimated from the measured data (red triangles in Fig. 6) by the Inverse Problem technique.

Fig. 8. Axial field decay with different trapped fields; Black line: a field cooling from the 0.1 T external field; Red squares: 0.25 T; Blue circles: 3.00 T. Time scale is adjusted for ease of comparison.

Figures 7 and 8 illustrate the temporal stability and axial distribution of trapped fields under different cooling conditions. The results suggest that a 40-mm long stack of 500 YBCO square plates (YP500) can provide a relatively homogeneous field distribution, with a center hole of 25 mm in diameter. A cryocooled 5-T LTS magnet was used to provide an external magnetic field to the YP500, field-cooled at 77 K. A trapped field of a single plate was measured and compared with computation. Also, the spatial distribution and temporal stability of trapped fields in various field-cooling modes were investigated and theoretically analyzed. Based on measured and analysed data, we summarize the conclusions as follows:

- In a square YBCO plate with a hole, peak trapped fields occur at the four corner edges of the hole. In order to minimize tesseral harmonic errors from noncircular currents following in the square plate, a serrated stacking method was adopted.
- The nickel substrate in the YBCO plate reduces the trapped field at the center of a hole, particularly in low fields. The effect of the nickel substrate on spatial field homogeneity in YBCO-stacked NMR magnets needs to be further studied.
- As trapped field in the YP500 becomes less than its maximum limit of capability, overall field homogeneity is improved because each plate’s current becomes gradually unsaturated and each plate can conserve more evenly the original flux of the external magnet having a relatively homogeneous field distribution.
- Individual critical current density of each of the 500 YBCO plates could be estimated from the measured trapped field by the Inverse Problem method with Evolution Strategy. The calculated field from the estimated current densities agrees well with measurement.
- Axial distribution of the estimated current densities in the YP500 is similar to that of the unsaturated trapped field with 0.076 T peak field; an optimized sequence of stacking order is required to further improve field homogeneity even in unsaturated trapped field conditions.
- As the trapped field becomes larger, the decay rate becomes faster. In a trapped field NMR magnet, an optimized field cooling procedure will be required to improve temporal stability as well as spatial homogeneity of trapped fields.

IV. CONCLUSION

The trapped field characteristics of a 40-mm long stack of 500 YBCO square plates (YP500) were investigated, experimentally and theoretically. Each square plate, $40 \times 40 \times 0.08$ mm, has

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