Progress in High-Speed Spin Testing of Superconducting Wire and Tapes for High-Field NMR Magnet Qualification

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Abstract. This paper summarizes the status of a 3-year, NIH-funded research project to study the strength of high temperature superconductors under high circumferential hoop stress, in order to qualify these materials for high-field (> 1 GHz-class NMR magnets. The unique approach presented here is to spin test coils at high rotational speeds, approaching 100,000 rpm, in order to induce the necessary hoop stress. Thermal strain compatibility between the Bi-2212 wire and Inconel wire has been qualified, including thermal cycling. Assembly and testing of the first low-speed (< 30,000 rpm) rotor is now in process, and the design of second, higher speed (> 60,000 rpm) rotor, is also underway.

1. Introduction

High-temperature superconducting (HTS) materials are an enabling technology for a new class (> 1 GHz) of NMR magnets due to their ability to transport large electrical currents in the presence of high magnetic fields beyond the limitations of low temperature superconductors (LTS). [1-7] As described in a previous paper [8], only the HTS types known as REBCO, 2212 and 2223 can break the LTS high-field (> 22 T) Je barrier.

A primary limitation in qualifying these HTS-based coils for high-field magnet use is the high cost and limited availability of high-field background magnets. Also, the room temperature bore size of these magnets is typically too small to accommodate the actual, full-scale size of NMR insert coils, which are typically wound on a 60-mm or 80-mm cold winding bore diameter to result in a 36-mm or 54-mm warm RT bore diameter, respectively.

As described in [8], a new spin test method has been proposed and developed to simulate the magnetic Lorentz stresses by imposing spin-induced circumferential hoop stresses.

The circumferential hoop stress, \( \sigma_h \), generated in a superconducting magnet winding, assuming a thin radial build, may be expressed in terms of the conductor current density, J, magnetic field, B, and radius, R, as:

\[
\sigma_h = J B R
\]  

From (1), the circumferential hoop stress for a 500 A/mm², 30 T at a winding radius of 0.03 m is 450 MPa. In a spin test, this same circumferential hoop stress, \( \sigma_h \), may be expressed in terms of the density, \( \rho \), angular velocity, \( \omega \), and radius, R, as:

\[
\sigma_h = \rho \omega^2 R^2
\]
From (2), the speed required to simulate this magnetic condition for a 3-in. diameter winding, or radius of 3.8 cm, is ~6300 rad/s, or ~60,000 rpm. This goal will be achieved in two steps—low-speed testing (up to 30,000 rpm) and high-speed testing (up to 60,000 rpm and higher). The initial low-speed testing will be conducting on the existing rotor shown in figure 1. This rotor consists of a 304 stainless-steel mandrel with a shrunk-fit aluminum arbor piece into which an Inconel spindle has been shrunk-fit for balancing and spinning.

![Photographs of: (a) Bi-2212 coil winding; (b) low-speed spin test rotor during shrink-fit process.](image)

**Figure 1.** Photographs of: (a) Bi-2212 coil winding; (b) low-speed spin test rotor during shrink-fit process.

After this initial low speed testing is completed and the test procedure has been qualified, a higher speed rotor will be fabricated consisting of an all-Inconel mandrel and arbor design, enabling the higher speed (> 60,000 rpm) capability.

### 2. Reinforced Bi-2212 Conductor

For this study, reinforced Bi-2212 wire, manufactured by Solid Materials Solutions in North Chelmsford, MA, will be used. Their patented version of 2212 wire consists of a rectangular, multifilamentary silver-based Bi-2212 conductor reinforced with top and bottom superalloy strips. The superalloy strips are bonded using a patented thermal diffusion bonding process.

Mechanical test samples of this conductor have been tested at Wentworth Institute of Technology using an Instron machine equipped with an infrared video extensometer, which can track the motion and strain of bonded white dots on the sample. This technique is well-suited for fine wires, as opposed to clipping on a bulky strain gage extensometer. Figure 2a shows a photograph of a typical test specimen, and a typical stress-strain curve is included in figure 2b.

### 3. Solid Nitrogen Test Station

One key development over this past year has been the development of a fully-automated solid nitrogen test station. This test station utilizes a National Instruments RMX-4124 power supply automated with LabView to measure the critical current of each sample. The required vacuum environment is created using a simple
glass Bell jar with a customized phenolic baseplate, equipped with the necessary current and instrumentation feedthroughs. A photograph of this set-up is provided in figure 3.

Figure 2. Reinforced Bi-2212 stress-strain: (a) sample photograph; (b) stress-strain curve.

Figure 3. Solid nitrogen test station: (a) computer-controlled power supply; (b) glass Bell jar set-up.

The main reason for using this simple Bell jar set-up is that it will enable much faster testing in between spin cycles at Barbour-Stock well. Also, the glass Bell jar allows visibility to ensure that the coil is adequately covered in sub-cooled nitrogen prior to testing, whereas a closed vacuum cryostat does not.
4. Test Coils

A. Single-Turn Coil Testing

Prior to mounting a superconducting winding onto the rotor, some initial single-turn coil tests were conducted in order to check that no degradation would occur due to the differential thermal contraction between the Bi-2212 conductor and the Inconel mandrel prior to spinning.

Single turns of 2212 conductor were bonded to a short section of Inconel tube and tested for critical current. These results summarized in figure 4 show that there was virtually no change in critical current after 10 thermal cycles.

A test coil using 6-mm wide, SuperPower 2G tape was also built and tested, also showing no degradation after thermal cycling. A section of this tape will also be bonded to the low-speed spin test rotor. Testing the 2G tape can be done in a simple liquid nitrogen environment due to its higher critical temperature.

B. Low-Speed Rotor Testing

The rotor shown in figure 1 is currently being prepared for balancing and spinning at Barbour-Stockwell. This rotor was made with an aluminum arbor, which connects the Inconel spindle to the 304 stainless mandrel. Using aluminum simplified the machining. The critical issue currently being addressed is the accurate positioning of the central Inconel spindle within the aluminum, so that the rotor can be balanced adequately. This process should be completed in early December 2019, so that the new coil can be installed on the rotor.

By spinning up to 30,000 rpm, the resulting stresses will be ~110 MPa (or ~16 ksi), according to (2). This testing will be accomplished in 5,000 rpm increments. Results from the initial low speed testing will be included in the paper after the conference and prior to publication.
C. High-Speed Rotor Testing

After the low-speed testing has been completed, lessons learned will be incorporated into the high-speed, fully-Inconel design, which will be fabricated next year. This rotor will be fabricated using Inconel 625, which has a yield strength of ~120 ksi, or ~840 MPa, enabling testing well beyond the required 60,000 rpm, or ~450 MPa.

D. Spin Test Procedure

The following is the proposed test procedure which will be validated on this low-speed testing:

1. Wrap rotor in thermal insulating jacket.
2. Slowly cool rotor in liquid nitrogen until fully immersed.
3. Quickly remove rotor from liquid nitrogen and install on spin turbine flange.
4. Remove thermal insulation jacket.
5. Seal spin pit chamber.
6. Pull vacuum.
7. Perform spin at desired speed.
8. Remove rotor from turbine.
9. Attach current leads and voltage taps to coil winding.
10. Set-up rotor in Solid Nitrogen Test station.
11. Slowly cool rotor until fully immersed.
12. Turn on vacuum until nitrogen solidifies.
13. Slightly back-off on vacuum until liquid forms again.
14. Perform critical current test.
15. Remove rotor from set-up.
16. Unsolder current leads and voltage taps.
17. Repeat for next spin test speed.

5. Thermal Insulating Jacket

A thermal insulating jacket was designed to maintain the rotor temperature while the spin rotor is being transferred into the spin pit. This blanket consists of a multi-layer aluminum radiation shield combined with a low-thermal conductivity Kapton foam insulating blanket. The blanket was sewn into an easy-to-disconnect cloth bag, as shown in figure 5a, allowing it to be easily removed prior to sealing the spin pit for vacuum.
The goal of this design was to maintain a rotor temperature of 100 K maximum prior to spinning. It is estimated that it will take ~5 minutes to mount the rotor in the turbine and seal the spin pit, so this sets the time limit requirement. After several iterations of this design, the students managed to achieve this goal, as shown by the data in figure 5b.

![Thermal insulating jacket: (a) photograph; (b) data.](image)

**Figure 5.** Thermal insulating jacket: (a) photograph; (b) data.

### 6. Summary and Conclusions

A new spin test method for qualifying superconducting wires and tapes for use in high field magnets has been proposed. The initial prototype low-speed spin rotor is currently being balanced in preparation for testing, which should occur in the December 2019-January 2020 timeframe. Subsequently, a higher speed, fully-Inconel rotor will be fabricated and tested towards the end of this 3-year, NIH-funded program, which ends in March 2021. If successful, this technique could prove useful for qualifying superconducting wires and tapes for > 30 T, high field magnets.

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