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Abstract— We are currently working on a program to complete a 1.5-T/75-mm RT (room temperature) bore MAS (magic-angle-spinning) NMR (nuclear magnetic resonance) magnet. The MAS magnet comprises a z-axis 0.866-T solenoid and an x-axis 1.225-T dipole coil. The combination of the fields creates a 1.5-T field pointed at 54.74 degrees (magic angle) from the rotation (z) axis. During the 2nd year of this 3-year Phase I program, both coils have been wound, and testing has been begun. Some preliminary field mapping has been performed, and the design and fabrication of the MAS magnet assembly has been completed. During the final year, the magnet assembly will be integrated into the cryogenic structure and tested at ~5.5 K in a solid nitrogen environment. Each coil will be energized separately, and the magnetic field will be mapped accurately. We expect a bare magnet uniformity of 100 ppm over a 10-mm diameter, 20-mm long cylindrical volume. Using the field data, the uniformity will be improved to <0.1 ppm with a combination of ferroshims and cryoshims. Final field measurement will be performed as the cryostat-magnet system is spun manually at ~0.1 Hz.

Index Terms— nuclear magnetic resonance (NMR), magic-angle-spinning superconducting magnet

I. INTRODUCTION

A rotating magic-angle field can be created either electrically or mechanically. In the electrical approach, the rotating field is achieved by a combination of a constant field in the rotation axis and a time-varying field normal to the constant field. While this approach has worked in a low-field (< 50 gauss) copper magnet, it is impossible to create a time-varying field approaching 1 T with a superconducting magnet, chiefly because of AC losses. In contrast, the mechanical approach uses a combination of two DC superconducting magnets that are rotated.

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Phase I has two specific aims: (1) build a superconducting magnet system comprising a z (axial)-field solenoid ($B_z$) and an x-y dipole ($B_x$), whose combined magic-angle field, $B_{ma}$, of NMR-quality and 1.5 T points at an angle of 54.74° (magic angle) from its spinning (z) axis; and (2) demonstrate an innovative cryogenic system that houses this superconducting magic-angle-field (MAF) magnet and to be rotated at 6 Hz in Phase II.

II. MAGNET DESIGN & ANALYSIS

The magnet design configuration is provided in Fig. 1. The design consists of a 3-part solenoid coil wound on a central stainless steel support tube onto which two opposing coils each comprised of two double pancake saddle coils are mounted. An iron yoke surrounds the assembly which is held between two end flanges.

Fig. 1—MAS magnet design concept.

Table I summarizes the coil design parameters for this magnet. The magic-angle field is 1.5 T, comprised of a
1.2247-T dipole field and a 0.8660-T solenoid field. We expect the magnet to have an as-wound field homogeneity of <100 ppm over a φ10-mm, 20-mm long cylindrical volume oriented along the magic-angle axis. Currently, we are developing a technique for active and passive shimming of the MAF by use of superconducting shim coils and ferromagnetic tiles to produce an NMR-field quality of < 1 ppm.

Magnetic field analysis was performed with the 2D FEMM magnetic field program. The field plot for the dipole is provided in Fig. , while the solenoid plot is shown in Fig. . For the dipole coil, the surrounding iron yoke significantly reduces the required ampere-turns by more than 30%, while creating a peak field of ~1.3 T in the iron itself, which is, as required, well below the saturation level of the 1010 steel plates. Although the solenoid coil adds a field to this dipole-induced field, the iron yoke field will still be below the nominal 1.5 T saturation level.

Fig. 2—Solenoid field plot showing the central 1.225 T uniform region.

Fig. 3—Dipole field plot, showing the 0.866 T uniform region in black.

III. STRUCTURAL ANALYSIS

An ANSYS 3D structural model was developed to analyze the stresses created by the solenoid-dipole interaction which generates an internal torque of ~1740 N m between the two coils. As shown in Fig. 2, the peak stress of ~70 MPa occurs in the solenoid support winding slots. This level of stress is acceptable for the stainless steel mandrel. The model analyzed the thermal contraction and effect of 6-Hz rotation. Table II gives a summary of these data.

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center magic-angle field (Bma)</td>
<td>[T]</td>
<td>1.5</td>
</tr>
<tr>
<td>Solenoid (axial, z) field (Bz)</td>
<td>[T]</td>
<td>0.8660</td>
</tr>
<tr>
<td>Dipole (x-y) field (Bx)</td>
<td>[T]</td>
<td>1.2247</td>
</tr>
<tr>
<td>Center field orientation</td>
<td>[degree]</td>
<td>54.74 from z-axis</td>
</tr>
<tr>
<td>Axial (spinning axis) RT bore</td>
<td>[mm]</td>
<td>75</td>
</tr>
<tr>
<td>NbTi insulated conductor width; thickness</td>
<td>[mm]</td>
<td>1.60; 0.85</td>
</tr>
<tr>
<td>OD of solenoid-dipole structure</td>
<td>[mm]</td>
<td>137.5</td>
</tr>
<tr>
<td>Overall coil length</td>
<td>[mm]</td>
<td>486</td>
</tr>
<tr>
<td>Overall wire length (dipole/solenoid)</td>
<td>[m]</td>
<td>740 / 260</td>
</tr>
<tr>
<td>Operating current (dipole/solenoid)</td>
<td>[A]</td>
<td>244.5 / 237.0</td>
</tr>
<tr>
<td>Rotation frequency about z-axis</td>
<td>[Hz]</td>
<td>~0.1 (Phase 1)</td>
</tr>
<tr>
<td>Operating mode w/ LHe transfer</td>
<td></td>
<td>persistent, continuous</td>
</tr>
<tr>
<td>Temperature range w/o LHe transfer</td>
<td>[K]</td>
<td>4.5 (nominal) 5.5 (limit)</td>
</tr>
<tr>
<td>Operation duration w/o LHe transfer</td>
<td>[hr]</td>
<td>~1.25</td>
</tr>
<tr>
<td>Homogeneity @ 100Φ X 20 MM</td>
<td>[ppm]</td>
<td>&lt;1 w/ ferro-shimming</td>
</tr>
</tbody>
</table>

IV. COIL FABRICATION

There will be four layers of windings in each dipole coil, each coil comprised of two double-pancake saddle coils wound on top of each other. This topology requires one persistent joint between each double pancake.

In our previous paper [1], we discussed the fabrication of a short-length version of these coils. Now, the first full-length double pancake coils have been wound. A photograph of this assembly being prepared for testing is shown in Fig. 3.
A simple winding machine, designed and constructed, formed this saddle coil into shape. The coils were wet-wound with Shell Epon 815 epoxy and wound at a winding tension of ~40 N. The torsional stiffness of the NbTi wire made it difficult to maintain the shape of the coil after winding. After several winding trials, we resolved this by bonding the underside of the first layer of the double pancake with a 0.5 mm-thick epoxy-glass layer. After this layer was fully-cured, the winding guides were adjusted, and the second layer of the double pancake was wound.

The solenoid coil shown in Fig. 4 has been completed and is ready for initial testing. This coil consists of three subcoils wound into separate slots. One continuous length of wire was used with crossover slots between each coil. This coil was also wet-wound with Epon 815 epoxy.

One joint will be required to connect the two double pancakes for each dipole. Also, one joint will be used between the two dipole coils and two more to connect the whole assembly to a persistent current switch.

The experimental setup for testing these coils at 4.2 K is shown in Fig. 5. This setup has been used for testing the critical current performance of both coils. The dipole coil was tested several times, including a final test up to 275 A at 1 A/s, showing no quench behavior. Fig. 8 shows a circuit used in these tests. Note that in actual operation, the dipole coil will be in persistent mode and its protection will rely on standard protection method for persistent-mode magnets [7].

Next, the second double pancake will be wound for each coil, and the assembly will be tested again, along with the solenoid coil.

Preliminary field mapping results were performed at 5 A in liquid nitrogen. For each test, the Hall sensor was mounted on an axial probe with the Hall sensor radially positioned 10 mm from the coil axis. These data (Fig. 9) show < 1% error between measurement and calculation. A resolution of ~0.1% is the limit of the Hall sensor in our measurement rig, but it at least provides a preliminary check of the field uniformity.

Once the dipole and solenoid coils with the iron yoke are assembled and operated at 4.2 K, a 3D mapping with a higher field resolution will be performed, in order to determine the shimming requirements. Then, a combination of ferromagnetic and superconducting shims will be employed.

The innovative cryogenic design concept discussed in previous literature [2-6] developed at MIT will be employed, in which the magnet will be immersed in solid nitrogen (SN2).
Fig. 5—Liquid helium test set-up.

Fig. 6—Circuit diagram for 4.2 K test setup.

Fig. 7—Field mapping results at 77 K and 5 A showing good agreement between measured values and pure cosine field profile.

This all-solid cold body ameliorates thermo-fluid issues associated with liquid under rotation. Also, solid nitrogen ensures a uniform temperature throughout the windings [2] and provides a large thermal mass, enabling the magnet to maintain its operating field over a time period even when a flow of liquid helium (LHe), its primarily cooling source, is shut off. The Phase I cryostat, due chiefly to a thermal mass of the 10-liter SN2, will have an estimated warm-up time period, from 4.5-K to 5.5-K, of > 1 hr.

VII. CONCLUSION

The fabrication and testing of an MAS magnet system is well underway, and the initial results look promising. The final assembly and testing of this magnet will be completed in Phase I, scheduled to end in August 2014. The test includes operation in persistent mode at 4.2 K and in the range 4.2-5.5 K under solid nitrogen cooling.

Accurate field mapping will be conducted with an NMR probe. Then, we will shim the field with a combination of superconducting shim coils and ferro shims. Both shims will be designed and built to enable them to withstand 6-Hz rotation, which takes place in Phase II.

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REFERENCES


