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Magic-Angle-Spinning NMR Magnet Development: Field Analysis and Prototypes

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Abstract

We are currently working on a program to complete a 1.5 T/75 mm RT bore magic-angle-spinning nuclear magnetic resonance magnet. The magic-angle-spinning magnet comprises a z -axis 0.866-T solenoid and an x -axis 1.225-T dipole, each to be wound with NbTi wire and operated at 4.2 K in persistent mode. A combination of the fields creates a 1.5-T field pointed at 54.74 degrees (magic angle) from the rotation (z) axis. In the first year of this 3-year program, we have completed magnetic analysis and design of both coils. Also, using a winding machine of our own design and fabrication, we have wound several prototype dipole coils with NbTi wire. As part of this development, we have repeatedly made successful persistent NbTi-NbTi joints with this multifilamentary NbTi wire.

Index Terms

Magic angle; magnet; nuclear magnetic resonance (NMR); spinning; superconductor

I. Introduction

MRI is one of the most powerful techniques to study body biology in a non-invasive three-dimensional manner. Currently, magnetic resonance imaging is limited to regions of homogeneous tissue (e.g., parts of the brain, breast) and does not offer its full potential in metabolism studies of other parts of the body (mainly those having an anisotropic morphology, e.g. muscles, lungs, bone structures, fibers, etc.) [1], because, for other parts of the body, the line-broadening is prohibitive for quantitative studies. The microscopic susceptibility cannot be shimmed, so it leads to a loss of information by spectral broadening [1]. The ultimate aim of this project is to extend the power of localized magnetic resonance scanning to anisotropic samples and apply this unique technique to all living matter.

The first magic-angle spinning-field experiment was performed by the UC Berkeley group [2], [3]. Their magic-angle-field magnet, a set of three orthogonal copper coil pairs, generated a spinning field of 36.3 gauss. Although the group next built a permanent-magnet-based 0.5-T magic-angle field magnet, they dwelled on shimming the non-rotating magnet and did not perform any NMR experiments [4]. When our project is successfully completed, the strength of the spinning field will be increased by greater than 400 times. A superconducting magnet is the only way to achieve this field enhancement.

In Fig. 1, two concepts for creating a rotating magic-angle field are depicted—electrical and mechanical. In the electrical concept, the rotating field is achieved by creating time-varying fields in the three coordinate directions. While this approach has worked in a low-field copper magnet, it is not possible with a higher field superconducting magnet, as the induced AC losses will surely quench the magnet. In contrast, the mechanical approach uses a combination of two DC fields.

During this past year, work has begun to develop this first-of-its-kind prototype magic-angle spinning (MAS) NMR magnet. 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 deg. (magic angle) from its spinning (z) axis; as shown in Fig. 1 and (2) demonstrate an innovative cryogenic system adopted for a rotating (0.1 Hz) low-temperature cryostat that houses this superconducting MAS magnet.

II. Magnet Design

Table I summarizes the coil design parameters for this magnet. The magic-angle field is designed to be 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 ϕ 10-mm, 20-mm long cylindrical volume oriented along the magic-angle axis. An NMR-field quality of <0.1 ppm will be achieved with a combination of superconducting and RT copper shim coils and ferromagnetic tiles.

A dipole field of 1.2247 T is achieved at an operating current of 369.24 A (air-core). With an iron yoke of thin steel annuli placed outside the dipole/solenoid assembly, the operating current is reduced to 219.70 A. Because this NbTi wire has a computed (based on 4.2-K data) critical current of 400 A at 5.5 K and 2 T (> maximum field within the winding), we expect the dipole magnet, epoxy-impregnated to minimize mechanical disturbances, to perform stably.

III. Coil Winding Development

Over the past year, the focus has been on the dipole magnet. A summary of the dipole magnet parameters is provided in Table II. The dipole coil winding tooling has been designed, fabricated, and tested with several test coils to fine-tune the winding machine, as with other tooling [5]. There are some unique features to this design, including the winding guide design. A photograph of this tooling setup is provided in Fig. 2.

Since there will be four layers of windings in each dipole coil, the preferred method is that each coil be comprised of two double-pancake saddle coils wound on top of each other. This topology requires one joint between each double pancake.

The aluminum winding drum, which can be manually rotated about its longitudinal axis, is set up on a rotary winding table. This setup allows the wire to be wound into a saddle-shaped, dipole coil by means of a system of guides. A stiffer backing plate and a flexible guiding strip are used in winding the dipole. Screws in the backing plate are gradually adjusted during the winding to make, by means of the flexible strip pressed on the winding, the winding conform accurately to the drum.

After developing the winding technique and tooling, we wet-wound with NbTi wire (2 mm wide $\times$ 1 mm thick) two practice dipole coils of 100 mm long (as opposed to 300 mm for the final design) straight sections. Each coil consists of a double-pancake with 62 turns per layer, whereas the final dipole will consist of two double pancakes wound on top of each other.

The two coils were mounted on a G-10 cylinder as shown in Fig. 3. The x -axis dipole field vs. z -axis position for this test dipole coil was measured using a Hall probe while immersed in liquid nitrogen and energized at 2.5 A; these results are plotted in Fig. 4(a). There is some difference in the absolute field values between the measured and calculated fields. This discrepancy may be due to some difference between the coil winding and the analytical model. For example, in such a short coil, it is difficult to determine the actual straight section length. However, when we normalized the center field values as in Fig. 4(b), the measured and calculated fields agree very well. Therefore, we feel that we are ready to wind the full dipole magnet coils.

After winding the dipole coils, the inner solenoid magnet will be wound. The parameters for the solenoid magnet are shown in Table III.

These two coils—dipole and solenoid—will be assembled onto a support structure and tested at 4.5–5.5 K. A more accurate spatial field measurement, involving a 3-D field scanner used for NMR magnets, will be performed for the dipole magnet.

IV. Cryogenic Design

An innovative cryogenics design concept developed at MIT will be employed, in which the magnet will be immersed in solid nitrogen (SN₂) [6]–[10]. This all-solid cold body ameliorates thermo-fluid issues associated with liquid under rotation. Also, solid nitrogen ensures a uniform temperature throughout the windings 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.

A schematic drawing of the Phase I cryogenic system is shown in Fig. 5. This system is comprised of a 43-cm cold bore “bucket” cryostat with a 75-mm RT insert and a cooling coil that houses the magnet chamber and a 10-liter SN₂ reservoir. In the vapor section above

the magnet, there is a stack of Styrofoam and radiation plates with the bottom plate thermally anchored to the cooling coil.

The LHe, from a storage dewar, is forced through the cooling coils to cool the cold assembly (magnet and SN₂) to 4.5 K. The return flow intercepts the heat conducted from the structural supports. In Phase I, with the LHe transfer line removed from the cryostat, it will be manually spun at ~0.1 Hz. The Phase I cryostat, due chiefly to a thermal mass of the 10-liter SN₂, will have an estimated 4.5-K – 5.5-K warm-up period of >1 hr. In Phase II, an entirely different motor-driven cryostat will house the cold assembly and be spun at 6 Hz.

V. Next Steps and Future Plan

The winding development for the dipole coil for the magic-angle spinning magnet has been completed. Next, we will begin winding the full-size dipole coils. After the dipole magnet is completed, the solenoid coil will be fabricated. Then, the two coils will be combined in a magnet assembly, complete with an iron yoke of thin steel annuli that serves as a return path and a shielding element for the magnetic field, and that also acts as a structural component.

During this development, we have repeatedly made successful, persistent NbTi-NbTi joints between multifilament NbTi wires. One joint will be required to connect the two coils for each dipole. Also, joints will be used between each dipole coil and to terminate the assembly.

Once the magnet assembly is completed, it will be assembled in the cryogenic support structure and cooled to 4.5 K with a flow of LHe. The dipole and solenoid magnets will be separately ramped up to their respective fields and put into persistent-current mode. With LHe flow stopped, the system will be manually rotated at ~0.1 Hz, and field measurements will be performed over a period of time up to ~1 h during which the SN₂ keeps the MAS magnet below 5.5 K and superconducting and the magic-angle field at 1.5 T.

After the initial field measurements, we will shim the field deploying a combination of superconducting and room-temperature (RT) coils and ferromagnetic tiles. Completion of Phase I is scheduled in August 2014. In Phase II, the 1.5-T, 75-mm RT bore slow-MAS magnet/cryogenic system will have a closed-loop helium system as the primary source of cooling. The magnet and SN₂ will be housed in a new cryostat that withstands 6-Hz rotation forces.

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References

1. Wind RA, Hu JZ. In vivo and ex vivo high-resolution ¹H NMR in biological systems using low-speed magic angle spinning. *Prog NMR Spectrosc.* Nov.2006 49, no. 3/4:207–259.
2. Meriles CA, Sakellariou D, Moule A, Budinger TF, Pines A. High-resolution NMR of static sample by rotation of the magnetic field. *J Magn Reson.* Jul.2004 169, no. 1:13–18. [PubMed: 15183351]
3. Sakellariou D, Meriles CA, Martin RW, Pines A. NMR in rotating magnetic fields: Magic-angle field spinning. *Magn Reson Imag.* Feb.2005 23, no. 2:295–299.
4. Jachmann RC, Trease D, Bouchard LS, Sakellariou D, Martin R, Schlueter RD, Budinger TF, Pines A. Multipole shimming of permanent magnets using harmonic corrector rings. *Rev Sci Instrum.* Mar.2007 78, no. 3:035115-1–035115-7. [PubMed: 17411225]

5. Brindza PD, Lassiter S, Fowler M, Milward S, Penfold P, Locke R, Allen R, Rajput-Ghoshal R. Coil winding experience for the Q1 super conducting quadrupole for the super high momentum spectrometer at jefferson lab. *IEEE Trans Appl Supercond.* Jun.2009 19, no. 3:1303–1306.
6. Yao W, Bascunan J, Kim WS, Hahn S, Lee H, Iwasa Y. A solid nitrogen cooled MgB_2 “demonstration” coil for mri applications. *IEEE Tran Appl Supercond.* Jun.2008 18, no. 2:912–915.
7. Haid BJ, Lee H, Iwasa Y. Thermal behavior of a solid nitrogen impregnated high-temperature superconducting pancake test coil under transient heating. *IEEE Trans Appl Supercond.* Mar.2001 11, no. 1:1852–1855.
8. Haid BJ, Lee H, Iwasa Y, Oh SS, Kwon YK, Ryu KS. Design analysis of a solid heat capacitor cooled permanent high-temperature superconducting magnet system. *Cryogenics.* Oct.2002 42, no. 10:617–634.
9. Iwasa Y, Bascunan J, Jankowski J, Kim HM, Lee H. Thermal and magnetic responses of a solid nitrogen/magnetized YBCO disk system undergoing temperature cycles in the range of 8–60 K. *IEEE Trans Appl Supercond.* Jun.2004 14, no. 2:1727–1730.
10. Bascunan J, Hahn S, Ahn M, Iwasa Y. Construction and test of a 500 MHz/200 mm RT bore solid nitrogen cooled Nb_3Sn MRI magnet. *Adv Cryogen Technol.* Apr.2010 1218, no. 1:523–530.

Fig. 1. Magnetic design concepts for creating a rotating magic-angle field: (a) electrical and (b) mechanical.

Fig. 2. Photograph of the MAS dipole winding tooling showing the guiding system consisting of rigid guides with flex strips.

Fig. 3.
Practice dipole coils mounted on G-10 tube.

Fig. 4. Field results for test dipole: (a) comparison of experiment and calculated results and (b) normalized comparison.

Fig. 5.
Schematic drawing of Phase 1 43-cm diam. cold bore cryostat and cooling scheme.

MAS Magnet Summary**Table I**

Parameter	Unit	Value
Center magic-angle field (B _{ma})	[T]	1.5
Solenoid (axial, z) field (B _z)	[T]	0.8660
Dipole (x-y) field (B _x)	[T]	1.2247
Center field orientation	[deg]	54.74 from z-axis
Axial (spinning axis) RT bore	[mm]	75
Rotation frequency about z-axis	[Hz]	~ 0.1 (Phase 1)
Operating mode w/ LHe transfer		persistent, continuous
Temperature range w/o LHe transfer	[K]	4.5 (nominal) 5.5 (limit)
Operation duration w/o LHe transfer	[hr]	~ 1.25
Homogeneity @ 10 × 20 MM	[ppm]	<1 w/ ferro-shimming

Table II
MAS Dipole Winding Summary

Parameter	Unit	Value
Conductor		
Width; Thickness (total with insulation)	[mm]	1.60; 0.85
Copper: Superconductor Ratio		7:1
Estimated critical Current @ 2T, 5.5 K	[A]	400
Coil Dimension		
Dipole Winding ID; OD	[mm]	125.0; 137.4
Dipole Overall Length	[mm]	486
Total Number of Turns (Turns/one pancake)		320 (80)
Number of Layers		
		4
Winding Section on Circumference	[deg]	120 + 120
Winding Pitch (Conductor Center to Center)	[mm]	1.55
Total Conductor Length	[m]	740
Iron Yoke (nominal dimensions)		
Inside Diameter	[mm]	150
Outside Diameter	[mm]	275
Stack Height		
	[mm]	600
Operation		
Operating Current (air-core)	[A]	369.24
Operating Current (with iron yoke)	[A]	219.70
Operating Temperature Range (Nominal-Maximum)	[K]	4.5-5.5
Field @ Magnet Center	[T]	1.2247
As-wound homogeneity over (110-mm; 20-mm long)	[ppm]	<100
Protection		
Estimated Inductance (with Iron Yoke)	[H]	0.41 (1.14)
Stored Energy (with Iron Yoke)	[kJ]	11.6(14.9)
T @ NZP = 5 m/s, Adiabatic (No Eddy-Loss)	[K]	<50K
Stress		
Estimated Peak Tensile Stress	[MPa]	<50

Table III
MAS Solenoid Winding Summary

Parameter		Coil 1	Coils 2-1; 2-2
Operating Temperature	[K]	4.5 (nominal);	5.5 (maximum)
Winding i.d./o.d./length	[mm]	105.0/111.0/49.0	105.0/113.0/57.0
Overall coil length	[mm]	0.0	+/- 57.5
Turns per layer/Layers per coil		49/3	57/4
Wire length per coil	[m]	49.9	78.1
Total wire length for Solenoid	[m]	206	
Operating current, I _{op}	[A]	257.0 (237.9)	
Total center field	[T]	0.866	
Total inductance (w/ iron yoke)	[mH]	18.2 (19.5)	
Total stored magnetic energy	[J]	600 (552)	
Field homogeneity	[ppm]	<100 (bare), <1 (shimmed)	