400 MHz / 89 mm ACTIVELY SHIELDED HIGH RESOLUTION NMR MAGNET

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Abstract—The first actively shielded high resolution NMR magnet was developed and successfully demonstrated. The magnet has excellent field homogeneity in a very large volume and lineshape characteristics exceed the specifications of the standard magnets. Shielding performance is also outstanding, with the 5 G line located only 1 m radially and 1.5 m axially from the magnet center. We are reporting the magnet specifications, details of the design and fabrication, magnet training, field mapping and lineshape results.

I. INTRODUCTION

High field NMR magnets normally produce strong fringe fields which can pose serious housing problems if space is limited. Construction modifications to accommodate conventional high field NMR instruments can be very expensive. Active shielding offers an alternative in these cases.

This paper discusses the development of an actively shielded NMR magnet operating at 400 MHz proton frequency and featuring a wide bore of 89 mm. The main coil of the magnet features three peripheral superconductive sections powered by reverse current in addition to the typical coil configuration of conventional unshielded magnets. These shielding sections generate an opposing magnetic field which cancels the stray field.

The magnet was designed to produce a very homogeneous field in a 40 mm diameter spherical volume which is more than seven times larger than the standard 14 mm diameter by 30 mm height cylindrical volume of conventional magnets. However, the amount of superconductor wire needed to accomplish the larger sweet-spot was increased. Another factor which increased the amount of superconductor is related to active shielding. Besides the actual superconductor wire used to wind the reverse current sections, more ampere-turns were needed in the direct current sections compared to a conventional unshielded magnet in order to compensate for the reduction in central field caused by the shielding sections. All these factors increased significantly the magnetic energy stored in the magnet. This created a challenge in

designing the quench protection system.

The axial physical dimensions of the magnet are the same as for a conventional magnet so that standard room temperature shim coils and NMR probes could be used.

The magnet passed all the standard tests and is presently operating at the UTMB at Galveston.

II. MAGNET SPECIFICATIONS

TABLE I
GENERAL SPECIFICATIONS OF THE MAGNET

Magnetic field in the center	9.395 T
Operating current	73.0 A
Operating temperature	4.2 K
Inductance	366 H
Stored energy	975 kJ
Field decay	< 7 Hz / hr
Room temperature bore	89 mm
Magnetic center to cryostat base flange	395 mm
Magnetic center to cryostat top flange	809 mm
Cryostat base flange to floor	805 mm
Cryostat diameter	1016 mm
Boil-off rate	
Liquid helium	50 cc / hr
Liquid nitrogen	210 cc / hr
5G line	
Radial distance from magnet center	1.0 m
Axial distance from magnet center	1.5 m

III. MAGNET DESIGN

A. Coil Design

The goal was to minimize the fringe field while achieving a very homogeneous field in the center. This was accomplished through an iterative process of magnetic field calculations performed with the computer program OPUS-2D which incorporates the structured coil technology [1]. This enabled us to find the optimal coil configuration to produce a magnetic field of desired strength at specified target points, with insignificant errors which were much smaller than the construction errors. The field simulation problem had three sets of target points. The first set of points was uniformly distributed along the surface of a 40 mm diameter sphere at the magnet center. The other two sets of points were uniformly distributed along the surface of an ellipsoid located outside the magnet in order to target the stray field in both axial and radial directions.

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Fig.1 The outline of the main coil and the magnetic field lines distribution.

Figure 1 shows the magnetic field lines as well as the outline of the main coil sections. The peripheral sections 6, 7, and 8 are wound in reverse direction thus carrying reverse current. These shielding sections create a magnetic field which opposes the stray field. The magnetic field lines are compressed in the region between the active shield and sections 3, 4, 5 due to the reverse current. All sections are connected in series and a superconductive persistent switch is connected in parallel with the main coil assembly.

Several construction errors were simulated and maximum tolerances were set for fabrication. Magnetic calculations determined the effect on the field homogeneity of the following types of errors: transition from one layer to the next one during winding, expansion of coils under magnetic forces, shrinking of coils during cool-down, axial and radial misalignment of the various coil sections, change in length and thickness of various coil sections, change in overall shape of various sections, low magnetization of the stainless steel coil forms and support plates. The error analysis was also useful in defining the specifications for designing the superconductive shim coils.

B. Mechanical Design

Structural analysis of coils and coilforms was performed using the program ALGOR. Stresses due to magnetic forces,

winding tension, and cool down of the magnet were considered in the simulation. The calculations were conservative and did not take into account the effect of the epoxy resin used for coil impregnation. The simulation results showed that the level of stresses induced by magnetic forces was low enough to avoid the use of overbanding for coil restraint. The calculations were used to design the cold mass and ensure its structural integrity. The main objective was to minimize the distortion of coils and coilforms during normal operation as well as during a quench.

C. Thermal Calculations and Cryostat Design

Detailed heat load calculations were performed for a proper design of the various cryostat subassemblies. The actively shielded magnet is larger in diameter and heavier than a standard magnet. Thus, the traditional support system using neck tubes could not be used because of the required increased thickness which would have significantly increased the heat load. A special suspension system based on s-glass support straps was designed to support the cold mass from three points located at 120 degrees from each other. A chain of straps was designed for each support line in order to minimize the heat load.

Figure 2. Cross section of the magnet cryostat.

The cryostat includes an intermediate thermal shield and a liquid nitrogen vessel. The nitrogen vessel is superinsulated with 30 layers of multi-layer insulation. The system includes inner intermediate and nitrogen shield tubes which were rolled and tack welded to avoid strong eddy currents which could be induced during a quench. The cross section of the magnet cryostat is shown in Figure 2.

D. Quench Protection and Electrical Design

The quench protection design followed a long iterative process of numerical simulations performed with a computer program [2] which is part of OPUS-2D. The program assumes adiabatic conditions for the magnet coil. It deals with inductively coupled coils and allows multiple independent fronts to coexist in the coils. Three parameters were essential in the quench simulation results: peak voltage, peak temperature, and fringe field levels. These were not to exceed certain maximum limits imposed by safety and operational considerations. Another important goal was to reduce the peak current in any of the sections.

The first few simulation runs identified sections 2, 4, and 5 to be the most critical ones. These are the most strongly coupled sections of the magnet.

Installing dump resistors across each of the sections and subdividing sections 2, 4, and 5 in two subdivisions each helped reduce the peak voltages [3]. Figure 3 shows the electrical circuit of the main coil. Sections 1 and 7 have two subsections each due to the limited spool length of superconductor wire. The electrical connection of subdivisions 4a, 4b, 5a, 5b, 7a, 7b, and 8 maintains the mid-plane symmetry of the magnetic field at all times, thus preventing unbalanced forces in symmetrical sections which could damage the magnet.

Figure 3. Magnet electrical scheme including the quench protection.

Quench heaters were used to reduce the peak temperatures in sections 2, 4, and 5. They were installed in thermal contact with the innermost and/or outermost layers of the critical sections. Each heater covers the whole length of the specified layers. Shortly after a quench occurs, enough power is deposited in the heaters to induce quenches at each turn of the layers in contact with the heaters, thus spreading the energy more uniformly within the specified coil sections and reducing the peak temperatures.

E. Main Coil Specifications

TABLE II
SPECIFICATIONS OF THE MAIN COIL SECTIONS

Parameter	Sec. 1	Sec. 2	Sec. 3	Sec. 4,5	Sec. 6	Sec. 7,8
Turns / Layer	460	732	118	373	98	114
Layers	24	38	38	38	30	30
Wire length (km)	6.036	21.03	4.288	13.555	6.611	7.692
Wire diameter (mm)	1.073	0.706	0.552	0.552	0.644	0.644
Cu / Sc ratio	1.35	2.0	3.0	3.0	7.0	7.0
Filaments	54	54	54	54	24	24
Peak field (T)	9.49	7.75	3.40	4.71	2.41	2.33
J_c (A / mm ²)	122.0	261.0	539.6	405.0	327.6	331.4
J_{op} (A / mm ²)	63.9	138.0	213.9	213.9	-173.1	-173.1
$J_{op} / J_c * 100$ (%)	52.4	52.9	39.6	52.8	52.9	52.3

III. MAGNET FABRICATION

The coilforms were fabricated from stainless steel. The main coil sections were wound from NbTi multifilament superconductive wire. They were vacuum impregnated with epoxy resin to prevent relative wire movements which could easily cause the magnet to quench. The main coil includes eleven superconductive joints which were individually tested. The superconductive shim coils were wet-wound from monofilament wire.

The radiation shields were fabricated from aluminum. The helium vessel and the vacuum vessel were fabricated from stainless steel.

Voltage taps were installed at each node of the electrical circuit in order to record the transient behavior of the voltages across each section during a quench.

IV. MAGNET TRAINING

The magnet quenched twelve times before it reached the full field current and the training curve is shown in Figure 4. Very good agreement was achieved between the experimental voltage plots and the numerical simulations, thus the origin of each quench could be identified.

Figure 4. Training curve.

Almost all quenches were initiated in either section 4 or 5. The first few quenches are believed to be caused by unbalanced forces due to small axial misalignments during magnet assembly. This is based on the decrease of the z1 residual gradient measured at half of the full field each time the magnet was energized. The rest of the quenches could have been caused by micro-cracks in the epoxy.

V. FIELD MAPPING

A. Central Field

Field mapping after shimming with the superconductive shim coils and before any room temperature (RT) shimming showed excellent field homogeneity. Figure 5 shows the field plot using the magnetic field values measured at 256 points on a helical trajectory over a cylinder of 14 mm diameter by 30 mm height.

Figure 5. Field plot on a 14 mm diameter by 30 mm height trajectory.

Figure 6. Non-spinning lineshape of a 5 mm sample of 1% CHCl_3 and 99% d_6 .

After reasonable RT shimming using a standard Oxford 18 channel shim set the non-spinning lineshape characteristics from a 5 mm sample were outstanding and exceeded by far the specifications. The linewidth at half of the full height for

the 1% CHCl_3 (chloroform) and 99% d_6 (deuteroacetone) solution was only 0.3 Hz and it was 2.9 Hz / 5.5 Hz at 0.55% / 0.11% of the full height, as shown in Figure 6.

B. Fringe Field

The radial locations for the stray field lines were determined by field measurements every 10 cm axial distance from the center. The stray field plots of the actively shielded magnet compared with the conventional unshielded magnets of the same strength are shown in Figure 7. The space volume of the 5 G stray field is reduced by a factor of 22.5 using the actively shielded magnet.

Figure 7. Stray field plots of 400 MHz / 89 mm magnets.

VI. CONCLUSION

The first 400 MHz wide bore actively shielded NMR magnet has been successfully demonstrated. The magnet met and even exceeded the specifications of a standard magnet of the same strength. The shielding performance is outstanding, with the 5 G line located only 1 m radially and 1.5 m axially from the magnet center.

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