Design of a 9.4 T Superconducting Magnet for 400 MHz Nuclear Magnetic Resonance

Yong Ren, Da Li, and Yuquan Chen

***Abstract*—A 9.4 T/400 MHz superconducting magnet with a warm bore of 60 mm is being designed. The 400 MHz NMR magnet is composed of 9 coaxial coils to generate a central field of 9.4 T. The magnetic field homogeneity is better than 4 ppm for 50 mm diameter spherical volume (DSV) and better than 1 ppb for 5 mm DSV. Three types of NbTi strands were used to reduce the cost of the superconducting materials. A preload with 80 MPa was exerted on the superconducting coils and over-banding with stainless steel was adopted to release the stress from the electromagnetic forces. The magnet will be operated in persistent-mode with superconducting joints to reduce the field decay. The pulse tube cryocooler with a cooling capacity of 1 W at 4.2 K can be used to reduce the liquid helium evaporation and vibration during operation. The magnet will be equipped with Bi2223/AgAu HTS current leads to reduce the heat losses.**

In this paper, the design of the 9.4 T NMR superconducting coils, electromagnetic field calculations and stress analysis of the superconducting coils were presented.

***Index Terms*—Magnetic field homogeneity, NMR coil, Superconducting magnet, Stress.**

I. INTRODUCTION

NUCLEAR magnetic resonance (NMR) instruments are widely used in analytical chemistry, biochemistry and structural biology to characterize the material properties, and in quantum information processing for quantum communication, quantum computing, and quantum simulation [1], [2]. Superconducting magnets are commonly used to generate a high magnetic field for desired magnetic field homogeneity within a volume of interest (VOI). High magnetic field NMR instruments can improve the sensitivity and chemical shift dispersion [3]. However, high-field NMR instruments are mainly limited to specialized labs due to their enormous costs and high-tech equipment requirements. The moderate magnetic field 400 MHz NMR instruments with dynamic nuclear polarization technique have proven to be one of the most cost-effective tools with low-cost components and excellent performance to study the mass-limited samples [1]. The R&D of moderate field NMR magnet is essential for industrial applications.

Moderate magnetic field 400 MHz NMR instruments are commonly developed using the NbTi low temperature superconducting superconductors. Higher magnetic field NMR magnets require expensive HTS REBCO tapes [4, 5]. Even generating 400 MHz NMR magnets via REBCO tape is still expensive [6]. The disadvantage of the NbTi superconductor is its low critical temperature and critical current density at a high magnetic field. Once the magnetic field is above 10 T at 4.2 K, the critical current will rapidly decrease. Q. Wang *et al.*, designed a 9.4 T/400 MHz superconducting magnet with a complicated structure to realize the liquid helium recondensing [7]. Therefore, the maximum magnetic field was limited to 9.6 T to improve the operating margin and its stability. To improve the magnetic field homogeneity, multi-layer windings will be used to facilitate the coil positions. This paper will present the magnet design and mechanical behavior analysis of a 9.4 T/400 MHz NMR magnet.

Manuscript received September 14, 2022. This work was supported in part by the Anhui Provincial Natural Science Foundation for Distinguished Young Scholars under Grant No. 2108085J27, the National Natural Science Foundation of China under Grant No 51406215.

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TABLE I
Specification of the 9.4 T/400 MHz NMR magnet.

Superconductor		NbTi
Central magnetic field	T	9.40
Maximum magnetic field in windings	T	<9.6
Room bore available	mm	60.00
Magnetic field uniformity (5 mm DSV)	ppm	<0.1
Operating temperature	K	4.2
Cooling capacity with PTR at 4 K	W	1
Operating current	A	<150
Long term field decay	ppm/h	0.1%

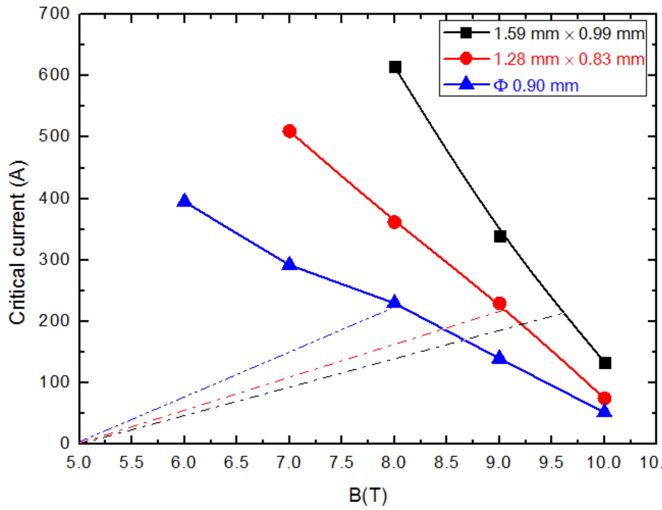

Fig. 1. Critical current of the NbTi wires as a function of magnetic field.

II. DESIGN OF A 9.4 T/400 MHZ NMR MAGNET

The 400 MHz NMR instrument requires a central magnetic

 doi:10.20944/preprints202207.0053.v1

TABLE II
Main parameters of the 9.4 T/400 MHz NbTi magnet.

Coil		1	2	3	4	5	6	7	8	9
Strand dimension	mm	1.59*0.99	1.28*0.83	1.28*0.83	0.90	0.90	0.90	0.90	0.90	0.90
Inner radius	mm	52.00	60.10	66.20	81.35	110.45	141.10	141.10	141.10	141.10
Outer radius	mm	58.10	65.20	71.35	98.45	136.10	158.20	158.20	147.95	147.95
Low Height	mm	-374.50	-374.50	-374.50	-374.50	-374.50	-374.50	207.00	-78.30	24.60
High height	mm	374.50	374.50	374.50	374.50	374.50	-200.70	374.50	-24.60	78.30
Operating current	A					105.5				
Engineering current density	MA/m^2	64.97778	96.278	95.3434	135.2532	135.2532	135.6032	135.6032	135.3722	135.3722
Layer		6	6	6	20	30	20	20	8	8
Turns per layer		469	581	581	821	821	191	191	59	59
Central field contribution	T	0.4928	0.6086	0.6069	2.8259	4.1405	0.1848	0.1848	0.1798	0.1798
Maximum magnetic field	T	9.5776	9.0881	8.4776	7.8759	4.9779	3.5003	3.5003	0.6850	0.6850
Inductance and strored energy	H/MJ					55.92 H/0.3112MJ				

field of 9.4 T with a warm bore of 60 mm. A superconducting magnet system must produce a multi homogeneous region with various magnetic field homogeneity for multi-purpose applications. The magnetic field homogeneity should be better than 0.1 ppm over a 5 mm DSV. The NMR magnet will operate at liquid helium at 4.2 K. To reduce the refill helium routinely and reduce the vibration during operation, a pulsed tube refrigerator (PTR) will be used [8]-[10]. The magnet needs to be operated in a persistent mode to limit magnetic field decay by using the superconducting joint. The maximum field decay should be less than 0.1 ppm/h [11]. Table I lists the specification of the 9.4 T/400 MHz NMR magnet.

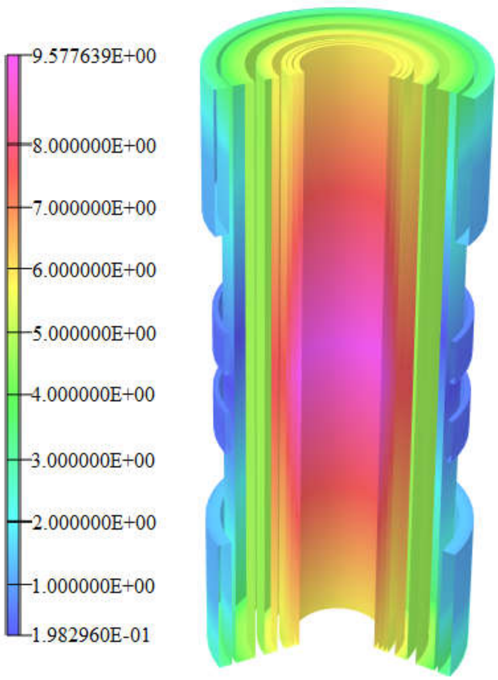

Fig. 2. Magnetic field distribution of the 9.4 T superconducting magnet.

The NbTi superconductors will be adopted for 9.4 T/400 MHz NMR magnet to reduce the costs of the superconducting material. To improve the operating temperature margin, the maximum magnetic field in windings should be less than 9.6 T. Three types of NbTi superconducting strands were adopted for manufacturing the magnet. Fig. 1 shows the critical current of the NbTi wires as a function of a magnetic field. A multilayer windings design was proposed to regulate the inhomogeneity in the special VOI. The evolutionally algorithm will be adopted to optimize the coil size and positions. Linear programming and nonlinear programming were used to optimize the coil size and positions [12].

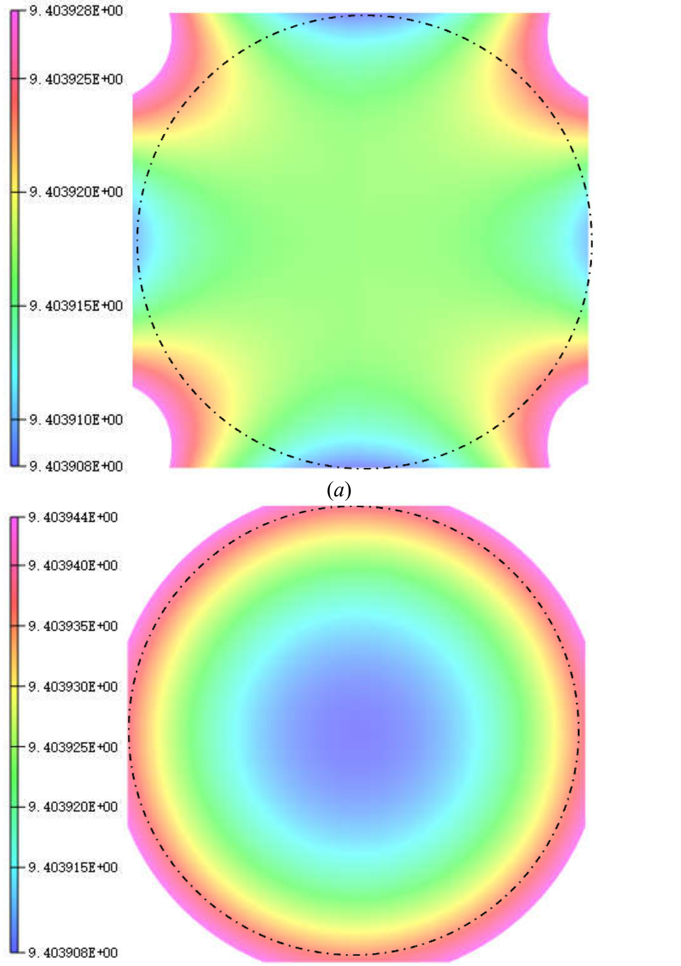

Fig. 3. Magnetic field distribution for the 40 mm DSV, (a) along the XZ plane, (b) along the XY-plane.

Table II lists the main parameters of the 9.4 T/400 MHz magnet. The optimized superconducting magnet was composed of 9 NbTi coaxial coils. A 2 mm spacer thickness was placed on the interval between the coils 1 and coil 2 to improve the magnetic field homogeneity. The magnet will generate a center magnetic field of 9.4 T at 105.5 A. The maximum magnetic fields for Coil 1, Coil 2 and Coil 4 are 9.5776 T, 9.0881 T and 7.8759 T, respectively. The stored energy of the superconducting magnet is about 0.3112 MJ at 105.5 A. The magnetic inhomogeneity is better than 4 ppm for 50 mm DSV and 0.8 ppb for 5 mm DSV. Fig. 2 shows the magnetic field

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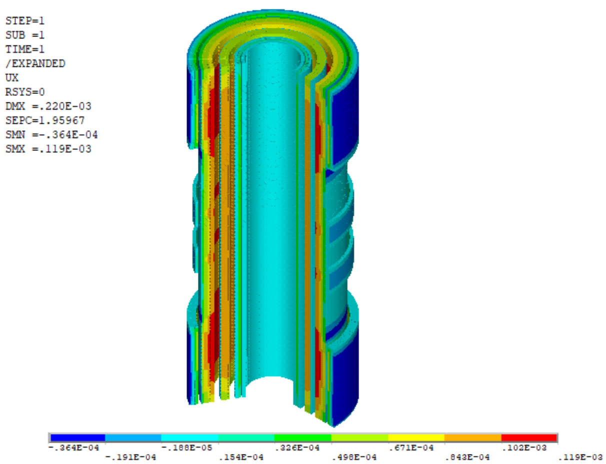
distribution of the magnet. Fig. 3 shows the magnetic field distribution for the 40 mm DSV along the XY plane and XY plane, respectively. Table III lists the magnetic field homogeneity for multi-regions.

TABLE III
Magnetic field homogeneity for multi-regions.

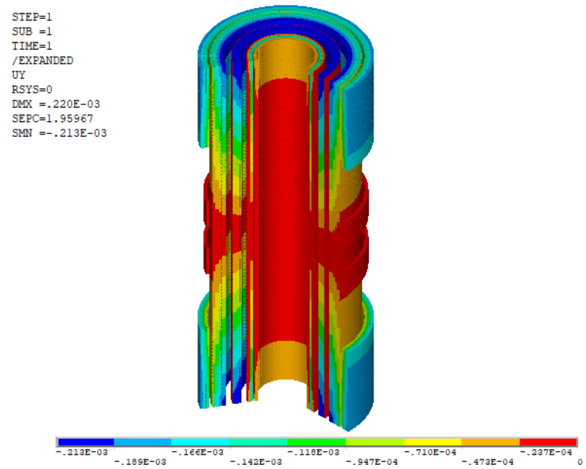
Homogeneous region (DSV)	Inhomogeneity
50 mm	3.935 ppm
40 mm	1.595 ppm
30 mm	0.507 ppm
20 mm	0.133 ppm
10 mm	2.565 ppb
5 mm	0.707 ppb

III. Mechanical Behavior Analysis of the 9.4 T/400 MHz Superconducting Magnet

The 9.4 T/400 MHz superconducting magnet will experience large stress from the electromagnetic forces. During the energizing of the superconducting coils, magnetic forces compress them coils azimuthally towards the mid-plane and radially against the external support structure. The finite element method with a contact model was used to evaluate the mechanical behavior of a superconducting magnet [13]. In this contact model, the contact pairs with 169 and 172 elements between the superconducting strands, and between the strands and steel were created [14]-[16]. Fig. 4 shows the radial and axial displacements of the superconducting coils due to the electromagnetic forces. The maximum Von-Mises stress from the electromagnetic loads is about 101 MPa, which was located at the coil 3, as shown in Fig. 5. Thus, the superconducting coil requires the preload to resist the electromagnetic loads. The winding stresses of the superconducting coils with 80 MPa were exerted during magnet manufacturing. The overbanding force with 180 MPa was exerted on the 304 stainless steel wires.



(*a*)



(*b*)

Fig. 4. Radial (*a*) and axial (b) displacements of the superconducting magnet from the electromagnetic loads (Unit: m).

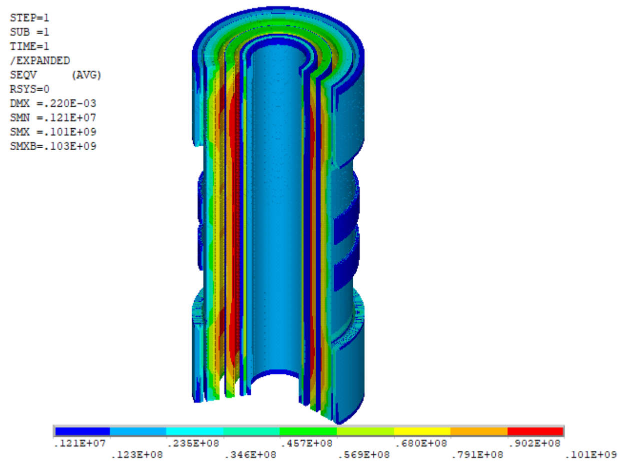


Fig. 5. Von-Mises stress of the superconducting coils from the electromagnetic loads (Unit: Pa).

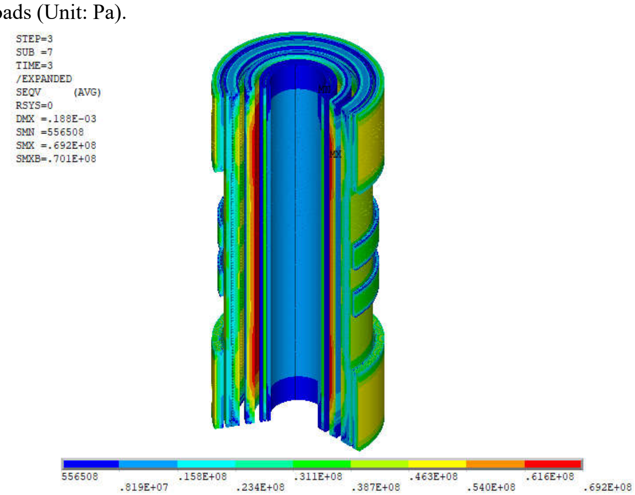


Fig. 6. Von-Mises stress of the superconducting coils by considering the winding, cooldown and excitation (Unit: Pa).

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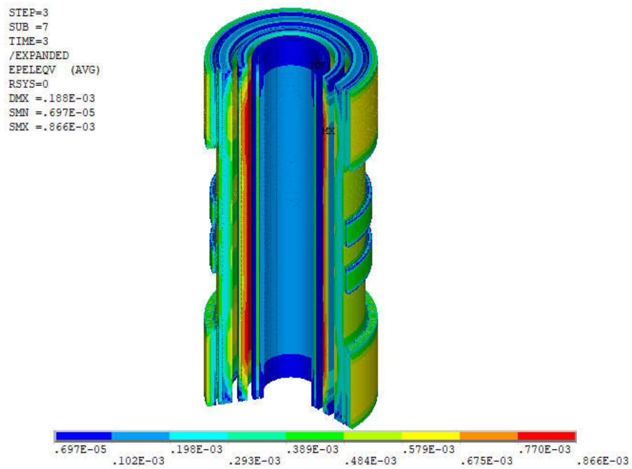

Fig. 7. Equivalent strain of the superconducting coils by considering the winding, cooldown and excitation.

IV. Quench Analysis of the 9.4 T/400 MHz Superconducting Magnet

The Superconducting magnet needs to be protected in the event of a quench. A passive quench protection method will be adopted to avoid the damage during a quench event. The 9.4 T/400 MHz superconducting magnet is grouped into three subdivisions to limit the coil voltages during a quench. The symmetrical coils are grouped together to prevent the imbalance magnetic forces. The initial temperature of 4.2 K was imposed on the whole coils of the superconducting magnet. To initiate a quench, the heating resources was added on the innermost layer of the coil-1.

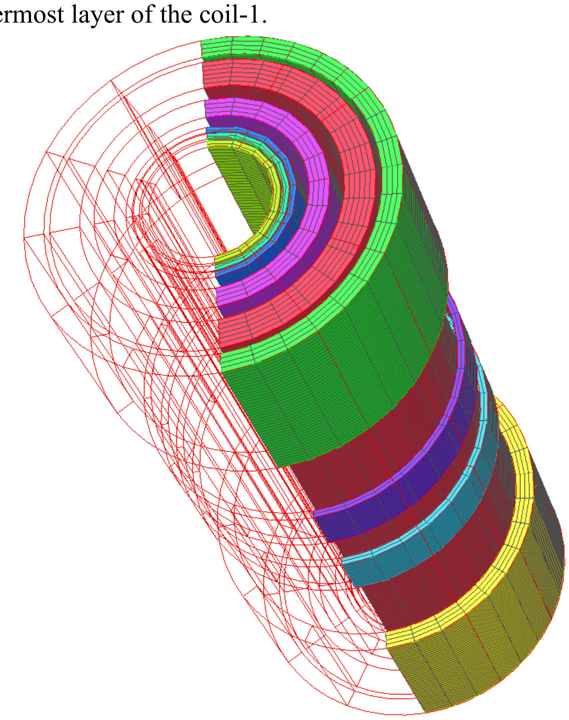

Fig. 8. Finite element modelling of the 400 MHz NMR magnet for the quench analysis.

The non-linear material properties for thermal conductivity, specific heat, and resistivity were considered. In addition, the thermal conductivity and electrical conductivity of copper dependent on magnetic field are considered for the quench analysis. The normal zone propagation in 3D directions in combination with the highly non-linear material properties make the quench propagating solution time consuming. The adaptive time step was adopted, and the minimum time-step was set to 1 ms to ensure the solution convergence. Fig. 8 shows the finite element modelling for the quench analysis. Fig. 9 shows the quench protection circuit of the 9.4 T/400 MHz superconducting magnet. The analysis results showed that the maximum hot temperature is about 100 K, which is well below the 150 K hot spot temperature criteria.

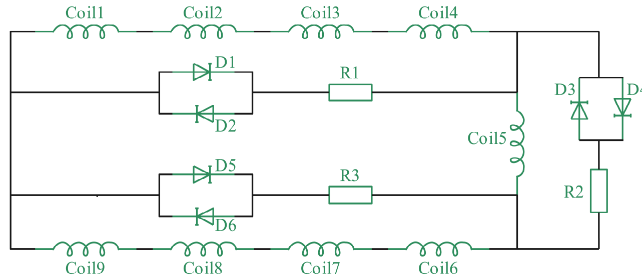

Fig. 9. Quench protection circuit of the 9.4 T/400 MHz superconducting magnet.

V. Conclusion

A 9.4 T/400 MHz NMR magnet with room bore of 60 mm by using the NbTi superconductors was designed with linear and non-linear programming. The 9.4 T magnet is composed of 9 coaxial superconducting coils wound with three types of superconducting strands. The inductance and the stored energy of the magnet are 55.92 H and 0.3112 MJ respectively. The magnet has the peak-to-peak magnetic field homogeneity better than 0.1 ppb for 5 mm DSV and 4 ppm for 50 mm DSV. The stress and strain of the superconducting coils were also calculated to evaluate their mechanical behavior. The magnet is being designed to operate in a persistent mode with an NbTi superconducting joint and switch to improve its stability of the magnetic field.

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