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A 1.3 GHz NMR Magnet Design under High Hoop Stress Condition

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***Abstract*— NMR magnets using high-T_c superconductors (HTS) to generate high magnetic fields exceeding 25 T are currently being designed by several organizations. In these designs, the HTS is used for the inner coils, and the other coils consist of NbTi and Nb_3Sn wires. The YBCO wire, which is a typical HTS, has excellent critical current performance over a wide range of magnetic fields and tolerates high tensile stress of up to 700 MPa. These properties make it possible to realize a high-field NMR magnet. In particular, the superior mechanical strength allows for the high-stress criterion of the electromagnetic force to be applied to the design of the magnets. In this study, we show the conceptual design of 1.3 GHz (30.5 T) NMR magnets under the condition of high hoop stress of 500 MPa. To achieve high magnetic field homogeneity in these designs, we propose three magnet design plans that have different arrangements of the compensation coils. We assumed that the magnet would be operated by the driven mode at 4.2 K. We also considered the strong angular dependence of the critical current of the YBCO wires to design the magnet.**

***Index Terms*— electromagnetic force, hoop stress, HTS, NMR magnet, YBCO.**

I. Introduction

Recently, the highest field of nuclear magnetic resonance (NMR) magnets has reached 1 GHz (23.5 T) [1]. This magnet was developed using low-T_c superconductors (LTS) and operated in the persistent mode at 2 K. However, a dramatic increase of the magnetic fields using LTS is considered to be very difficult to achieve over 23.5 T because the critical fields of LTS have a small margin against the peak fields of the magnet.

Using HTS is considered to be the only solution to dramatically increase the highest fields of NMR magnets because of their high critical fields. The HTS will apply to the manufacture of a 1.3 GHz (30.5 T) NMR magnet [2]. At present, Bi-2223 and YBCO conductors are promising for practical applications [3]. Although Bi-2212 conductors have been developed, a stable fabrication process for Wind & React coils has not been established because of the difficulty of conducting a homogeneous heat treatment [4]-[6].

The performance of the 2nd generation (2G) YBCO wires fabricated by the IBAD process on the Hastelloy substrate has been improved [7]. The features of the 2G YBCO have excellent critical current performance over a wide magnetic field range and tolerate high tensile stress up to 700 MPa [7]. In fact, the engineering critical current density (J_e) of this wire is 1000 A/mm^2 over 30 T at 4.2 K as shown in Fig. 1 [8]. In addition, the insert coil made with the YBCO succeeded in generating 33.8 T in a 31 T axial background field provided by the NHMFL facilities [7]. These results show that it is possible to manufacture a high-field magnet practically exceeding 30 T using YBCO.

Incidentally, the fact that the high-stress criterion of the electromagnetic force applies to the design of the high-field magnet has been pointed out [9]. In the design of the magnet, which relied on conventional LTS (NbTi, Nb_3Sn), the stress criterion was limited to 200 MPa at most. However, assuming that YBCO is mainly used, it will be possible to design a high-field magnet under the high-stress criterion of 500 MPa. Owing to our model coil calculations, the coil volume of the 500 MPa criterion decreases to about 1/40 of that of the 200 MPa criterion. This calculation may be an ideal case and may actually never be realized. However, it is a fact that the high-stress criterion will result in a more compact and economical magnet design.

In this study, we show the conceptual design of 1.3 GHz NMR magnets used by YBCO mainly under the condition of the high hoop stress of 500 MPa. To achieve high magnetic field homogeneity in these designs, we propose three magnet design plans with different arrangements of the compensation coils. We assumed that the magnet would be operated by the driven mode at 4.2 K. We also considered the strong angular dependence of the YBCO wires as shown in Fig. 2 to design the magnets [10].

II. Design Criteria of 1.3 GHz NMR Magnets

We assumed the following criteria to design 1 GHz (30.53 T) NMR magnets.

- We used YBCO superconductors for main coils. In a certain design, NbTi was applied to the compensation coils only.
- As the relationship between B and J_e, the data shown in Fig. 1 were applied [8].
- In the angular dependence of J_e, we applied the typical

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relationship at 4.2 K and 12 T shown in Fig. 2 [10]. It was assumed that this angular dependence would be valid in the entire designed field region.

- The maximum hoop stress (σ_h) defined by $B_z \times J \times r$ was about 500 MPa.
- The inner diameter of the innermost coil is 80 mm to provide the ϕ 54 mm room temperature bore (so-called a narrow-bore NMR magnet).
- The coil length was limited to 1800 mm in reference to the 920 MHz NMR magnet length of 1520 mm [11]. This length was decided to simplify the compensation coil made with YBCO because a longer coil can achieve high homogeneity easily.
- Considering the actual manufacture, each coil thickness and the clearance among the coils were roughly fixed to 60 mm and 10 mm, respectively.
- The thickness of the wire was 0.1 mm, and the maximum width was limited to 12 mm by the fabrication facilities.

The YBCO wire was used only as the tape conductor because of the physical deposition process. Therefore, we decided to only change the wire width for the grading technique when designing the magnets. Electric insulation of the wire is necessary to wind the coil. In the reinforced Bi-2223 wire fabricated by Sumitomo Electric Industries, Ltd., the polyimide film (0.025 mm thickness) is half-wrapped around the wire for the electric insulation [1 2]. The insulation thickness was assumed to be 0.05 mm.

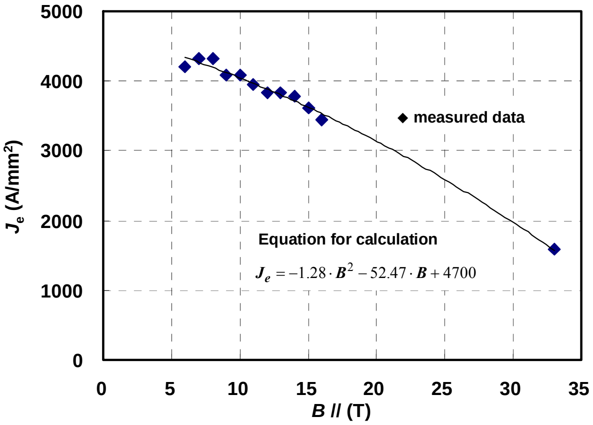


Fig. 1. Magnetic field dependence of the engineering current density (J_e) of YBCO at 4.2 K. The measured values [8] and approximate curve for the calculation are shown.

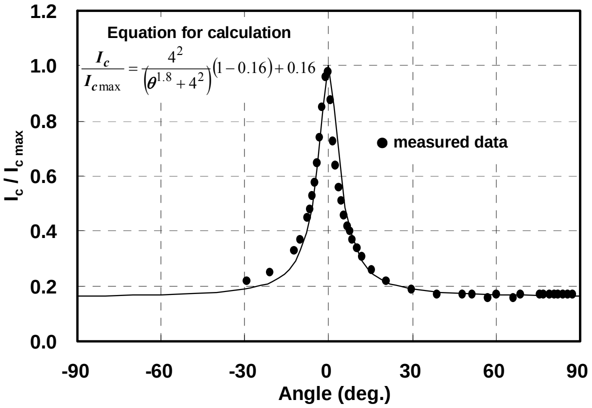


Fig. 2. Angular dependence of thecritical current of YBCO at 4.2 K and 12 T. The measured values [10] and approximate curve for the calculation are shown.

In recent experiments using an HTS coil, it was proved that sufficient NMR data were measured under the driven-mode operation [13]. In the coil design, it was assumed that the magnet would be operated in the driven mode at 4.2 K. Therefore, we did not consider the small intrinsic resistance of HTS and the joint resistance among the wires in this study.

III. MAGNET DESIGNS OF 1.3 GHZ NMR MAGNETS

We considered three magnet design plans of the 1.3 GHz NMR magnet. The cross-sectional view and the coil parameters of each magnet are shown in Table I and Fig. 3, respectively. The strength of the σ_h in each coil is drawn by the solid line in Fig. 3. In the case of LTS NMR magnets, the margin of the operating current (I_{op}) to the critical current (I_c) is usually decided at the highest field point in each coil section. However, owing to the strong angular dependence of the YBCO, the operating margin should be calculated by considering the decrease of the I_c by the field angle. In these cases, the highest points of the ratio I_{op}/I_c (shown by ☐) do not coincide with the maximum field points (shown by ★). They are located at the coil edges near the highest field angle. While the field angle is less than 8 degrees in the innermost coil, it is approximately 90 degrees in the outermost coil. Although the I_c diminishes to 16 % of the maximum value at a 90-degree field angle, the ratio I_{op}/I_c of the outermost coil is approximately 33 %. This means that these designs are appropriate as for the critical current, although the techniques controlling the magnetic field angle, such as the flux corrector, are not used.

Generally, the magnetic field distribution can be described by the spherical harmonics function. The axial magnetic field is described by the following series while considering the symmetry of the configuration.

$$B_z(z) = B_0 + B_2 z^2 + B_4 z^4 + B_6 z^6 + --- \quad (1)$$

To achieve a high field homogeneity magnet, the coils are arranged to reduce the 2nd and 4th order coefficients (B_2 and B_4). Coefficients greater than the 4th order such as B_6, are insignificant because the main coils are sufficiently long.

In the type-A magnet, the outer compensation coil made with NbTi wire is applied to achieve the high field homogeneity. The B_2 and B_4 coefficients at 20 mm diameter spherical volume (DSV) are 0.0001 ppm and -0.006 ppm respectively. Although this type is a very conventional configuration, it has high feasibility. The advantage is that the YBCO coils have a simple solenoid shape. Therefore, the YBCO main coils can be manufactured not only in the double-pancake method but also in the tight-winding method.

The shape of the type-B magnet does not have a notch or prominent section. The 2nd innermost coil is divided into 5 parts that have different current densities. The changes of the current densities eliminate the B_2 and B_4 coefficients for high field homogeneity, such as the outer compensation coils. This type-B magnet will be made by stacking double-pancake coils using different width conductors of 11.5, 10.6, and 11.48 mm. In this case, the σ_h in the parts of the narrow conductor becomes

TABLE I COIL PARAMETERS OF EACH MAGNET

(a) Type-A magnet that use the compensation coil made with NbTi

		#1	#2	#3	#4	#5
Superconductor		YBCO Bare wire thickness: 0.1 mm				NbTi
Bare wire width	(mm)	9.80	11.50	12.00	9.54	∅0.9
Coil inner diameter	(mm)	80.0	221.6	363.2	504.8	646.4
Coil outer diameter	(mm)	201.6	343.2	484.8	626.4	680.6
Coil length	(mm)	990.0	1392.0	1790.8	1793.0	71.3
Coil center position	(mm)	0.0	0.0	0.0	0.0	+/- 353.3
Number of turns		30400	36480	44992	56544	1350
Wire length	(km)	13.4	32.4	59.9	100.5	5.6
Maximum magnetic field	(T)	30.5	22.2	15.1	8.7	3.1
Maximum field angle	(deg)	7.4	15.6	51.6	89.9	89.9
Field homogeneity	(ppm)	B_2= 0.0001, B_4= -0.006 at 20 mm DSV				
Weight	(kg)	YBCO=1942 and NbTi=27				
Operating current	(A)	217.17				
Inductance	(H)	1628				
Stored energy	(MJ)	38.4				

(b) Type-B magnet in which the 2nd coil is divided into 5 parts with different current densities.

		#1	#2a	#2b	#2c	#3	#4
Superconductor		YBCO Bare wire thickness: 0.1 mm					
Bare wire width	(mm)	9.80	11.50	10.60	11.48	11.90	9.10
Coil inner diameter	(mm)	80.0	221.6	221.6	221.6	363.2	504.8
Coil outer diameter	(mm)	201.6	343.2	343.2	343.2	484.8	626.4
Coil length	(mm)	990.0	371.2	149.8	393.7	1776.0	1748.0
Coil center position	(mm)	0.0	0.0	+/- 260.5	+/- 532.3	0.0	0.0
Number of turns		30400	9728	4256	10336	44992	57760
Wire length	(km)	13.4	8.6	7.6	18.3	59.9	102.6
Maximum magnetic field	(T)	30.5	22.3	22.3	21.9	15.1	8.2
Maximum field angle	(deg)	7.2	0.3	2.0	17.4	55.9	89.8
Field homogeneity	(ppm)	B_2= -0.0006, B_4= 0.011 at 20 mm DSV					
Weight	(kg)	1930					
Operating current	(A)	216.07					
Inductance	(H)	1623					
Stored energy	(MJ)	37.9					

(c) Type-C magnet in which the innermost coil is notched.

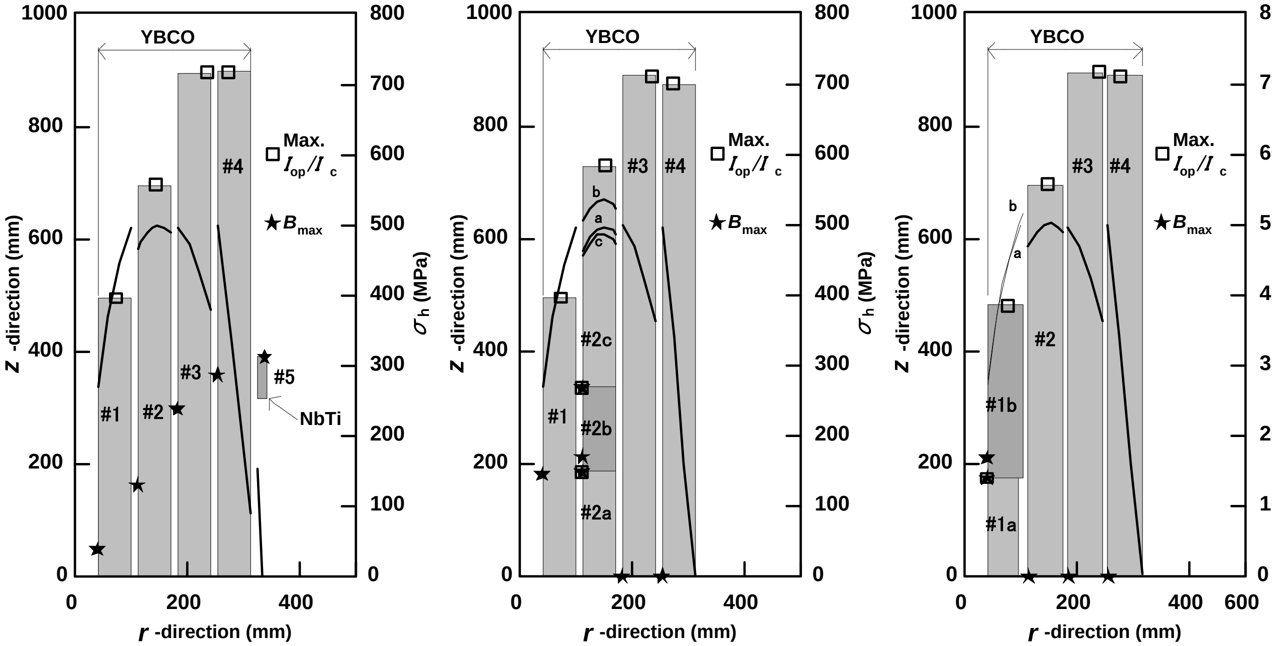
		#1a	#1b	#2	#3	#4
Superconductor		YBCO Bare wire thickness: 0.1 mm				
Bare wire width	(mm)	9.60	9.49	11.50	12.00	9.06
Coil inner diameter	(mm)	80.0	80.0	228.0	369.6	511.2
Coil outer diameter	(mm)	201.6	208.0	349.6	491.2	632.8
Coil length	(mm)	349.2	306.9	1392.0	1790.8	1777.0
Coil center position	(mm)	0.0	+/- 328.0	0.0	0.0	0.0
Number of turns		10944	10240	36480	44992	58976
Wire length	(km)	4.8	9.3	33.1	60.8	106.0
Maximum magnetic field	(T)	30.6	30.6	22.1	15.0	8.2
Maximum field angle	(deg)	0.7	7.6	15.6	53.9	89.8
Field homogeneity	(ppm)	B_2= -0.014, B_4= 0.028 at 20 mm DSV				
Weight	(kg)	1963				
Operating current	(A)	215.27				
Inductance	(H)	1669				
Stored energy	(MJ)	38.7				

536 MPa, which is larger than the σ_h of the other section.

In the type-C magnet, the innermost coil is the outer notched shape, which is stacked in double-pancake coils with different width (9.60 and 9.49 mm) and different layers (304 and 320 layers) for high field homogeneity. In the double-pancake method, inaccurate positioning when stacking pancake coils caused poor field homogeneity. Therefore, this method has not yet been applied to an actual NMR magnet. However, it may be effective to take advantage of the characteristics of tape conductors and achieve high field homogeneity without using the conventional compensation coil as well as the type-B.

IV. CONCLUSION

We attempted to design 1.3 GHz NMR magnets using YBCO mainly under the condition of the high hoop stress of 500 MPa. Our results suggest the possibility to realize more compact and light-weight magnets than the conventional magnet with LTS and HTS. In our design, the conductor weight of about 2000 kg is less than one half of the 920 MHz NMR magnet [11].



(a) Type-A (b) Type-B (c) Type-C

Fig. 3. Cross-sectional view and hoop stress shown by the solid line of each magnet.

On the other hand, the following problems remain to be solved.

- The magnet inductances exceed 1600 H. Although the value is not so much higher than that of the 920 MHz NMR magnet (1123 H) [11], the quench protection circuit should be considered for safe operations. The quench back protection system or the active protection method might be effective.
- The application of the high-stress criterion causes high axial compressive stress inside of each coil. The highest value becomes about 120 MPa at the axially central plane in the outermost coils. Therefore, detailed electromagnetic stress analyses should be carried out. This is very important especially for the double-pancake method.
- The problems of the screening current in the HTS coil during energization have been pointed out [14, 15]. The magnetization induced by the screening current will cause the long-term drift of magnetic fields as well as field inhomogeneity.

Although many problems need to be solved before YBCO is applied, the properties for the design of a high-field NMR magnet are very attractive and are the most applicable for the achievement of a 1.3 GHz NMR magnet.

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