Improvement in field uniformity of the hybrid insert magnet

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Abstract. The hybrid magnet (HM) at the Tsukuba Magnet Laboratory (TML) generates 35 T in a 52-mm warm bore with a field uniformity of about 6500 ppm in a 10 mm diameter sphere volume (DSV). A new resistive insert magnet with the same bore was designed to provide the higher field uniformity in the HM operation and the construction was started. This magnet is composed of three concentric Bitter coils. The height of the outer coil is almost equal to that of present insert. The middle coil is made of a split-paired winding: The split gap is 53 mm. The field uniformity better than 10 ppm in a 10 mm DSV will be achieved at a magnetic field of 34.0 T in a backup field of 14 T. This improvement in uniformity, in conjunction with the improvements of the DC power supply already in progress at the TML, will make it possible to expand the application fields of the HM of the TML.

1. Introduction

NMR measurements are one of the most promising applications in high magnetic fields. Various superconducting nuclear magnetic resonance (NMR) magnets are in operation around the world. Presently, the maximum magnetic field generated by a superconducting magnet is about 23 T at present [1]. And the cost of the NMR superconducting magnet rises dramatically when approaching this magnetic field limit. The NMR magnets are available with the dedicated DC power supply system and the cooling system, as they consume a huge amount of electrical power.

The Tsukuba Magnet Laboratory (TML) designed and began to manufacture a new resistive insert magnet with a 52-mm warm bore for the 34 T hybrid magnet (HM) by altering the constitution of the resistive insert for the 35.5 T HM, in order to meet the requirements of an NMR study in high magnetic fields. In November 2004, the TML fabricated a 52-mm warm- bore resistive- insert magnet (called 5235N#1 hereafter) for the HM and generated a peak magnetic flux density of 35.5 T at an operating current of 34.88 kA and 367.5 V with a background field of 14.02 T from the outsert [2].

Since that time, the TML HM with the 52-mm warm- bore resistive magnet has been in use for most of the machine time of the TML HM. Now, this insert magnet was replaced with a newly constructed insert of the same design in size as of the warm bore, including the outer diameter and the magnet height. This new insert magnet (called 5235N#2 hereafter) generates a magnetic field that is approximately equivalent in peak field to that generated by the previous insert 5235N#1. The on- axis uniformity of the magnetic field around the center is also similar to that of the 5235N#1. Consequently, this homogeneity is also far lower than those of resistive magnets built for low- resolution NMR [3]. To getobtain higher on- axis field homogeneity.
in the TML HM, of the middle coil of resistive insert 5235N#1 was remodeled the designed by introducing a split coil.

2. Resistive insert for 35.5 T HM
The renewed resistive insert 5235N#2 for the 35.5 T HM consists of three concentric Bitter coils. The cooling holes of the Bitter disks are elongated and arranged for a the staggered distribution [2]. Disks are punched using the same die sets that were as used for the disks of 5235N#1, though the lot number of the Cu-Ag plates is a different one and Cu-Cr plates (0.7 and 0.8 mm in thickness) are used for the outermost Bitter coil. The difference in the finished coil height in every layer is 0.5 mm at the maximum between 5235N#2 and 5235N#1. The on- axis homogeneity of the insert magnetic field without an outsert field of HM is worse than 650 ppm at the a point which left 5 mm from the insert magnet center. This insert magnet will supply a conventional magnetic field in HM.

3. Design and constitution of the revised insert
There are already reports that Bitter magnets having with a split magnet in the middle layer show possess higher field homogeneity and have been working well, and manufacturing tolerances for the alignments of the coils are relatively not tight so severe [3]. This method was introduced into the remodeling for the improved uniformity insert magnet (called 5234S#1 hereafter). The composition of the 5234S#1 is almost the same as that one made in the TML, other than the existence of except for the split region in the middle layer ( B coil ) of the three- layered concentric coils. Figure 1 illustrates the configuration of the modified resistive insert is shown in Figure 1. The dimensions and electrical- power distribution were determined within the constraints coming arising from the mechanical, electrical and thermal properties of the materials for the coil; and the properties of the DC power supply and cooling systems; and the superconducting outsert magnet (SM) of HM [2], including the restrictions mentioned below. The height of the split region is determined considering manufacturing tolerances. Bitter disks of the same cooling- hole pattern and the same type of end plates that ose work as electrodes were used in the insert magnets 5235N#1, 5235N#2 and 5234S#1 in order to obtain the improved field homogeneity by the simple modification of disk stacking, and to make reduce the coil manufacturings at the low cost. Consequently, the height of the outermost coil is the same as that of the 5235N#2 in order to use existing parts for installing the magnet installation to the HM.

The parameters of the resistive insert 5234S#1 thus determined are listed in Table 1, along with the properties of the materials used for the disks of each layer of the Bitter coil. The innermost Bitter Disks are made of the Cu-Ag alloyed plates. Cu-Cr alloyed plates are used for the middle and the outermost Bitter coils. The disk thickness of the middle coil is a little thicker than the other TML insert coils.

![Figure 1. Layout of the Bitter coils and configuration around the coils of the resistive insert. In the middle coil B, there is a split region 53 mm in height.](image)
4. WM field profile

The on-axis field profile of the resistive insert 5234S#1 in the perfect alignment is shown depicted with the symbol WM in figure 2 together with those of SM and HM. Each line represents the on-axis field variation of each magnet for the field of each at the magnet center. The on-axis magnetic field of the SM falls down even in the vicinity of near the magnet center. We chose a magnetic field profile of the 5234S#1 as shown in the thick broken line in figure 2 to compensate for this rapid on-axis field decrease when leaving from the magnet center in the SM. The split of the middle Bitter coil is 53 mm in height.

In the poly Bitter coil, the difference in the magnet center of the constitutional coils, between the actual location and the designed location is apt to remain even after the geometrical adjustment of the magnet center, though that is compensating for the asymmetricity of current distribution in the coils. This displacement causes the degradation of the on-axis field homogeneity.

To estimate the degree of the effect by the on-axis displacement of coils for on the field homogeneity

| Parameters | Coil A (innermost) | Coil B (middle) | Coil C (outermost) |
|------------|-------------------|----------------|-------------------|
| Inner radius (mm) | 29.0 | 78.0 | 121.0 |
| Outer radius (mm) | 75.5 | 120.0 | 170.0 |
| Height (mm) | 216.0 | 395.5 | 405.0 |
| Field (T) | 11.08 | 5.01 | 3.60 |
| Material | Cu-Ag | Cu-Cr | Cu-Cr |
| UTS (MPa) | 942 | 624 | 520 |
| %IACS | 76 | 76 | 89 |
| Stress (MPa) | 619 | 475 | 244 |
| Power (MW) | 4.82 | 5.98 | 2.08 |
| Voltage (V) | 137.8 | 231.0 | 231.0 |
| Current (kA) | 34.95 | 26.00 | 8.95 |
| $J_{max}$ (A/mm²) | 490 | 243 | 104 |
| Max. Temp. (°C) | 94 | 81 | 45 |
| Hole nNumber of holes | 160 | 144 | 312 |
| Tie rods | 16 | 24 | 24 |
| Disks/turn (main) | 8 | 8 | 3 |
| Turns (main) | 57 | 77 | 157 |
| (end region total) | 2 | 4 | 2 |
| Disc Thick. (mm) | 0.43 | 0.48 | 0.80 |

Figure 2. On-axis field variation of WM, SM and HM. The twin-peak profile of WM is to account for tolerance in the installation into the SM.

Figure 3. Distortion of the on-axis field profile by the displacement of the coil center of the resistive insert 5234S#1. Coils B and A are displaced axially x mm and 2x mm with respect to coil C.
within the poly Bitter coil, three cases of the displacement is fixinging the outermost coil at a designed place location were calculated. The assumed axial displacement of the middle coil is +x mm with respect to the outermost coil, and that of the innermost coil is +2x. The plus sign shows indicates that the supposed displacement is up ward with respect to the center of the outermost coil. Examinations were conducted ed for the values x=0.4 mm, x=0.6 mm and x=0.8 mm.

Figure 3 shows illustrates the resulting eddeviation of the on- axis field profile from that of a theperfect alignment of 5234S#1. The on- axis field profile of 5234S#1, though it has twin peaks,, maintains a relatively homogeneous range, against the increase in the degree of on- axis plus x coil displacement, on the above region above of the center of the outermost coil.

5. HM field profile
The perfectly aligned insert 5234S#1 brings achieves on- axis field homogeneity of 2 ppm over the 5 mm axial range if the centers of the SM and insert 5234S#1 are isaligned perfectly. A rather homogeneous profile will be realized in the upper ward, region of the SM center even if the center of the perfectly aligned insert 5234S#1 is displaced axially up to about 2 mmon the above.

For the HM with the insert 5234S#1 which has the (on- axis displacement (+x, +2x ; x = 0.4 mm in figureure 3) among the Bitter coils), the on- axis homogeneity of the HM (=SM+WM) decreases to about 60 ppm over the 10 mm axial region. Figure 4 shows depicts the variation of the expected on-axis field profile of the TML HM with the insert 5234S#1 that contains with this displacement (+x, +2x ; x = 0.4 mm) for the on- axis distance between the center of the SM and that of the insert 5234S#1 (center of C coil). By adjusting the placement of the insert magnet, a magnetic field of 33.7 T in a 52 mm RT bore with a homogeneity of 10 ppm over a 10 mm axial region is at least expected using 14 T SM and 12.9 MW of power.

6. Summary
M A modified resistive insert magnet was designed and started. to production is being carried out in the TML. This insert 5234S#1 is expected to generate a magnetic field of 33.7 T in a 52 mm RT bore with the a homogeneity of 10 ppm over a 10 mm axial region using 14 T SM and 12.9 MW of power. This field uniformity, in conjuncllaboration with theimprovements of the DC power supply of the TML, will expand the application fields of the TML HM.

References
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