Superconducting properties of experimental YBCO coils for FFAG accelerator magnets

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Abstract. A project to develop fundamental technologies for accelerator magnets using high-$T_c$ coated conductors is currently in progress. The target applications of this project are fixed field alternating gradient (FFAG) accelerators for carbon cancer therapy systems and accelerator-driven sub-critical reactors. Several types of superconducting coils for FFAG accelerators have been conceptually designed. These coils have complicated shapes, including a negative-bend part or a three-dimensional bent part. One of the aims of the project is to establish winding technologies for complicated coil shapes using coated conductors. To demonstrate winding technologies for YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) coils, small test coils having a negative-bend part or a three-dimensional bent part were designed and fabricated according to the present design of the FFAG magnet. The outside dimensions of the negative-bend test coil were 460 mm long and 190 mm wide, and the radius of curvature of the negative-bend part was 442 mm. The outside dimensions of the three-dimensional test coil were 380 mm long and 280 mm wide, and the radius of curvature of the mandrel of the three-dimensional coil was 700 mm. The test coils were wound using YBCO coated conductors with a length of about 100 m and were then impregnated with epoxy resin. The coils were placed in liquid nitrogen and excited to measure their $V$–$I$ characteristics. From the $V$–$I$ characteristics throughout a voltage range down to $10^{-9}$ V/cm, the $V$–$I$ characteristics before and after impregnation were approximately the same, demonstrating that the superconducting properties were not degraded.

1. Introduction

A project to develop fundamental technologies for accelerator magnets using high-$T_c$ coated conductors is currently in progress [1]. The target applications of this project are fixed field alternating gradient (FFAG) accelerators for carbon cancer therapy and accelerator-driven sub-critical reactors (ADSRs). Several types of superconducting coils for FFAG accelerators have been conceptually designed in this project, such as a spiral sector superferric type and a radial sector coil-dominated type [2], [3]. The superconducting coils for these types have complicated shapes including negative-bend parts or three-dimensional bent parts. One of the aims of the project is to establish winding technologies for such complicated coil shapes using coated conductors. This paper describes the
fabrication and the test results of two coils, one including a negative-bend part and one including a three-dimensional bent part.

2. Coil designs for FFAG accelerators
The designed structures of the main rings of the spiral sector superferric type and the radial sector coil-dominated type FFAG accelerators for carbon cancer therapy systems are schematically shown in figure 1 and figure 2. The main rings are composed of a number of magnets and the outer diameters of the rings are approximately 10 m, which is about half the size of present ones. The spiral sector superferric type accelerator achieves strong focus by using edge-focusing [4]. For this reason, the coils have an inward winding part called a negative bend. The radius of curvature of the negative-bend portion is 2340 mm. In this type of accelerator, the magnetic field distribution required in the beam orbit can be optimized through appropriate design of the pole gap shape, and therefore, the superconducting coils can be built simply by winding the tape conductor flatwise into a pancake shape. In contrast, with the radial sector coil-dominated type of magnets, the magnetic field distribution is ensured by a precise suitable design of the coil shape, and a three-dimensional winding structure has been required. A schematic view of the designed coils is shown in figure 3.

3. Test coil fabrication
A coil having a negative-bend part suffers from the problem that, when a winding tension is applied, the coated conductor tends to come off the bobbin. The coated conductor needs to be fixed at the negative-bend part of the coil. [5]. To demonstrate winding technologies for YBCO coils with a negative-bend shape, a small test coil, of about one-eighth scale, was designed and fabricated according to the present magnet design. The specifications of the test coil are listed in table 1. To construct the test coil, we used a YBCO coated conductor with a width of 5 mm and an $I_c$ of 184 A (77 K, self field). The winding method is schematically illustrated in figure 4. Holding jigs were set to completely surround the bobbin. The tape was wound onto the bobbin by repeatedly removing and reapplying the holding jigs. Therefore, even if holding jigs in negative-bend part are removed, the coated conductor is restrained from coming off the bobbin because other jigs keep holding it in other area. The force of coming off the bobbin at the negative-bend part is increased in every turn. So, the force of applying the jigs was increased by using springs when thickness of coil increased. The coil was co-wound with a conductor composed of YBCO tape and polyimide tape for insulation and was then impregnated with epoxy resin. A photograph of the test coil is shown in figure 5. The mean thickness of the test coil is 31.5 mm, and the deviation of thickness of coil held down with 0.35 mm.

As shown in figure 3, the designed coils require a three-dimensional structure at the coil ends. On the other hand, YBCO conductor usually has a flat tape shape, and it is difficult to plastically deform the conductor in the edgewise direction. We designed the bobbin shape in such a way that the two edges of the tape wound along the bobbin follow curves of equal length, forming a constant-perimeter condition, without applying edgewise bending [6]. So, the innermost turn was the constant-perimeter...
condition. On the other hand, the outer turns were wound in accordance with the inner turn, and were diverged from the constant-perimeter condition. Therefore, stress occurred by the outer turns, and there was a possibility that the external coil shape was distorted from the shape of the outspread of the innermost turn. The coil end was separated into two blocks by a spacer as shown in figure 3. The second block coil was wound on the first block coil, and it had discontinuous connections in the coil end. On the premise of no deformation of the external shape of first block coil, the spacer, made of FRP, was manufactured in a curved surface calculated with the constant-perimeter condition. So, deformation of the external coil shape leads to a stress concentration or kinks around the discontinuous connections. In order to evaluate winding technologies for three-dimensional coils, we tried to fabricate a one-fourth scale test coil having a discontinuous coil end. Because of avoiding deformation, the conductors were fixed in places not to slide to the width direction, and the test coil was wound by the winding machine synchronizing the rotating and yawing motions. A 90-turn coil was wound on the bobbin with a 90 m length of 3 mm-wide YBCO coated conductor ($I_c$: 87 A at 77 K, self field), and an additional 40-turn coil was wound after setting the spacer. The specifications of the three-dimensional test coil are listed in table 2. The coil was co-wound with a conductor composed of YBCO tape and polyimide tape for insulation and was then impregnated with epoxy resin. A photograph of the coil is shown in figure 6.

![Figure 4. Schematic view of winding process.](image1)

**Table 1.** Specifications of the negative-bend test coil.

| Specification                          | Specification     |
|----------------------------------------|-------------------|
| Length of the test coil                | 460 mm            |
| Width of the test coil                 | 190 mm            |
| Radius of curvature of negative-bend   | 442 mm            |
| part                                   |                   |
| Number of turns                        | 100               |
| Length of conductor                    | 100 m             |

**Table 2.** Specifications of the three-dimensional test coil.

| Specification                          | Specification     |
|----------------------------------------|-------------------|
| Length of the test coil                | 380 mm            |
| Width of the test coil                 | 280 mm            |
| Radius of the mandrel                  | 700 mm            |
| Number of turns                        | 90+40             |
| Length of conductor                    | 140 m             |

![Figure 5. Photograph of the negative-bend test coil.](image2)

![Figure 6. Photograph of the three-dimensional test coil.](image3)

4. Test results
In a previous study, degradation of impregnated YBCO coils was observed, and we have previously reported that the performance of impregnated circular coils was improved by dividing the coils into a number of parts in the radial direction [7], [8]. To verify that this method can be applied to
complicated shaped coils, we measured the test coil’s $V$–$I$ characteristics before and after it was impregnated. The coils were cooled down carefully with liquid nitrogen for a few hours, and the electrical current was increased to observe the behavior of the voltage generated in the coil. The measured $V$–$I$ characteristics of the negative-bend test coil and the three-dimensional test coil are shown in figure 7 and figure 8. The $V$–$I$ characteristics before and after impregnation were approximately the same. Furthermore, an index values of as high as 30 were demonstrated all the way down to the low voltage region of $10^{-9}$ V/cm. The coated conductor wound into the shape of a coil having a negative-bend part or three-dimensional bent part exhibited superior superconducting properties, and the method of improvement reported in [7], [8] was suitable for the complicated shaped coils, too. These test results show that degradation-free superconducting properties were obtained and demonstrated the possibility that a coated conductor can be wound into a complicated shape for the magnet of a FFAG accelerator.

![Figure 7. $V$–$I$ characteristics of the negative-bend test coil.](image)

![Figure 8. $V$–$I$ characteristics of the three-dimensional test coil.](image)

5. Conclusion
Complicated coil shapes including a negative-bend part or a three-dimensional bent part were experimentally fabricated to evaluate the superconducting properties. The results of experiments showed that impregnated test coils were successfully fabricated and did not show any degradation in the superconducting properties. The results of the present study will promote the adoption of the winding technology described here, but further investigation will be required in order to consider the required field distribution in accelerators. We will continue our R&D into winding technologies for coated conductors in order to realize a larger prototype coil for further experiments in the future.

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