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Bipolar electrical coil based on YBCO bulks: Initial tests

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Abstract. In the field of the application of HTS in electrical motors, most prototypes are made using superconducting coils based on tape and located in the position where copper coils work in a similar conventional motor.

Other prototypes use superconducting bulks (usually disk-shaped) in those positions where normal magnets should work in similar conventional motors.

But it is very unusual to find designs using electrical coils based on bulks. This is a challenge whose main problem is the difficulty in machining the superconductor bulks to get the proper shape because of the impossibility of bending the material to wind coils.

The design of a bipolar single-turn coil made from a superconducting YBCO disk was proposed by the group of Electrical Application of Superconductors, at the University of Extremadura, several years ago to be an element for the design of a modular two-phase inductor for an air core axial-flux motor. The shape of each coil looks like an 'S'. When a current flows through the circuit, two opposite magnetic fields appear in the upper and lower halves of the piece.

Until now, attempts to get a good superconducting circuit by cutting a YBCO disk into the required shape have failed because of cracks appearing in the crystal during the process. Last year, our group at the University of Extremadura began to work with ATZ GmbH who have improved the machining process and made the coils.

In this paper we present the coil and the first tests carried out.

1. Introduction

Superconducting electrical motors represent one of the least developed applications in the field of superconductivity. The benefit of this kind of motor is only reached when its power is very high, and most projects involve very large budgets in large laboratories and electrical companies.

The simplest designs for superconducting rotating electrical machines locate the superconductor elements (tape coils or bulks) at the rotor [1-5]. This is the cool part of the machine and is refrigerated through the shaft. The stator works at room temperature and is made with conventional materials.

Other designs use superconductors in both rotor and stator. In this case the whole machine works inside the cryogenic container, which is a challenge for large machines.

In all cases one of the electrical parts of the machine is made with coils and the other can be made with coils or bulk. In the last case, the coils replace DC conventional coils or magnets.

No cases of coils made from bulks are reported in the literature.
Our proposal is to design a small motor with superconducting circuits made from bulks in both the rotor and stator.

The configuration of the motor is explained in section 2. In section 3, a brief description of the fabrication process of the coils is presented. In section 4, we present the study and initial tests of the magnetic field created by an individual coil alone and over a superconducting disk in the position of the rotor as we will explain.

2. Motor configuration
The proposed motor consists of an YBCO superconducting disk, working as a rotor, located in a rotating magnetic field parallel to the axis. The magnetic field is created in the stator by AC currents in superconducting coils like those in figure 1. In order to give the maximum symmetry to the system, the stator is divided into two semistators located on each side of the disk. Each semistator consists of a pair of two-pole, single turn coils $\frac{\pi}{2}$ rad out of phase (see figure 1). No ferromagnetic medium is included in the design.

![Figure 1](image.png)

**Figure 1.** Arrangement of the motor. The magnetic field is created in the two-phase stator by a two-phase current system, resulting in a rotating magnetic field that pulls the rotor.

In spite of our group has proposed this configuration time ago [6], it was impossible to get adequate coils to assemble the motor and during this time, the effects of the magnetic field over the disk were studied [7].

3. Fabrication process of the coils
The superconducting coils are pieces of 50 mm diameter fabricated by ATZ, Germany.

The material is based on top seeded melt textured YBCO single crystal growth method. Sm123 crystals are placed on the top surface of the pressed YBCO samples followed by heat treated melt processing. Finally, oxygenation is performed at a temperature of about 400°C in pure oxygen during a time of 200 hours.

The processed YBCO single grain bulks have a diameter of about 55 mm and show at 77 K trapped field values of typically 0.8 T at 1.4 T excitation. The values are smaller than those of ATZ’s standard magnetic material. Under comparable conditions 65 mm $\times$ 33 mm multiple (3) grain YBCO tiles can trap more than 1 T indicating the well known drop of $J_c$ with increased domain size.

Before machining each block was evaluated and investigated by magnetic properties and especially referring to mechanical stability. A perfect $c$ axis melt textured crystal possesses a low tensile strength in $c$ direction and can be damaged easily even by applying small forces.

Hence, the raw samples were stabilized before and in intermediate steps during machining by a vacuum resin infiltration and impregnation.

The final shape is obtained using CAD programming and performing a numerical milling procedure with diamond milling tool at high rotational speeds. Even though the melt textured YBCO material is fragile and brittle in its morphology, by careful machining a mechanical precision of up to 10 $\mu$m was obtained. One of the fabricated motor elements is shown in figure 2.
To generate two magnetic poles, the circular conductor parts with a $5 \times 5$ mm$^2$ cross section are cut twice in a mirror-like symmetry in reference to the centre of the element. Solder wire connections are made by local copper galvanic deposition, followed by thermal treatment at moderate temperatures ($100^\circ$ C).

![Figure 2. One of the coils fabricated by ATZ. The indicated cuts are filled with resin to stabilize the piece mechanically.](image)

4. The magnetic field
As we measured previously [7], torques near 1 mNm can be reached in a superconducting disk working in a rotating magnetic field with a mean axial component of about 20 mT per pole. For this measurement a rotating magnet under the disk was used.

To get this magnetic field with the proposed stator, a two-phase current system of about 120 A RMS is necessary. A single coil with this current should give a mean axial magnetic field of about 7 mT per pole. This is only a rough estimate because the axial components depend on the shape of the field lines in the different positions of the field over time.

5. Measurement of the magnetic field
The experimental device used to measure the axial magnetic field component is shown in figure 3. It consists of a Hall probe that can be positioned in place by means of a Cartesian positioning system.

The coil was fed by a voltage generator adjustable both in amplitude and frequency, a power amplifier and a transformer that reduces the voltage and increases the current. The frequency for these tests was 10 Hz (with two poles, this frequency corresponds to a rotation speed of 600 rpm). The current was 60 A RMS because of some problems with the contacts heating.

A computer application based on the software Labview was developed to control the process. The steps after initially positioning the probe are:

- Take the measurement of a whole number of periods of the magnetic field (typically 5).
- Calculate and save the amplitude of the magnetic field waveform.
- Move the probe up to the following position.
- Take a new measurement and repeat the process.

The movement of the probe is with steps of 1 mm along the $x$ axis up to the end of the surface under test and then 1 mm along the $y$ axis followed by a new complete movement along the $x$ axis but in the contrary direction. The sequence is repeated to cover the entire surface.

The result is the map of the $z$ (axial) component of the magnetic field in the $x$-$y$ plane.

Two initial tests were carried out on the pieces made by ATZ:

- The magnetic field axial component map over a single coil. The probe covered a surface 1 mm above the coil that includes the entire coil.
- The magnetic field axial component map between a single coil and one of the disks destined to work as a rotor (see figure 3). The probe covered a surface 1 mm below the coil that includes a half of one of the poles of the coil. This is because in this case the screw in the hole prevents the probe from passing.
Figure 3. Experimental arrangement for the measurement of the magnetic field by means of an axial Hall probe. The image on the left shows the Cartesian positioning system used. At the right, there is a detail of the probe in a measurement position between the coil and a superconducting disk.

6. Results and discussion

Figure 4 shows the map corresponding to the first of the tests. The results are those expected in a coil of this the shape and size, independently of the material (superconducting or not).

The map resulting from the last test, when a superconducting disk was located just under the coil, is different (figure 5) mainly in two aspects:

- The amplitude of the measured magnetic field is greater than in the former test.
- The axial magnetic field presents a minimum in the centre of the pole. The values there are lower than in the former test in the same position.

This is due to the screening effect of the disk that groups the field lines in positions closer to the current, making the axial component higher both there and on the other side of the current, outside the coil, and lower at the centre of the pole.

One important question with respect to the magnetic field measured at the centre of the pole is what part of this is the axial component in the magnetic field lines closed between the coil and the disk and what part is trapped magnetic field in the disk. Both of the components need to be quantified in future tests because each one is responsible for a pulling mechanism on the rotor in this kind of motor.

7. Conclusions

A superconducting coil made from an YBCO bulk has been fabricated by ATZ and the initial tests carried out in the University of Extremadura.

The general magnetic behaviour of the coil outside the influence of another superconductor is independent of the material (superconducting or not). The advantage of superconductors is the possibility of reaching higher magnetic field without ferromagnetic support but some problems with the contacts between the coil and the feed wires remain to be solved.

Close to a superconducting medium with the same dimensions, the magnetic field increased in amplitude but presented a minimum at the centre of the poles.

Further tests have to be done to determine the trapped flux in the disk under AC magnetic field.
Figure 4. Map of the axial component of the magnetic field in a plane parallel to the 50-mm-in-diameter coil, 1 mm above it. The scale is from –3 to 3 mT. The map corresponds to the amplitude of the magnetic field with a current of 60 A RMS in the coil.

Figure 5. Map of the axial component of the magnetic field between the coil and a superconducting disk. The measurement was taken in a parallel plane, 1 mm below the 50-mm-in-diameter coil. The scale is from –5 to 5 mT. The map corresponds to the amplitude of the magnetic field with a current of 60 A RMS in the coil.

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