I. 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 [1]–[5].

On the contrary, other authors have studied low or fractional power motors [6]–[9]. Some of these motors [9] use YBCO bulks working in an axial magnetic field. The trapped magnetic field in the bulks used for these applications (having the same direction throughout the bulk) has been extensively investigated [10]–[12].

Our proposal is to design a small air-core motor with superconducting circuits made of bulks in both the rotor and stator. As a difference from the previous configurations, we use a rotating two-pole distribution of the magnetic field in the same superconducting bulk.

II. MOTOR CONFIGURATION AND WORKING PARAMETERS

The proposed motor consists of an YBCO superconducting disk of 4 mm thickness, 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 Fig. 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 $\pi/2$ rad out of phase (Fig. 1).

No ferromagnetic medium is included in the design. The superconducting coils are pieces of 50 mm diameter made of YBCO bulks and fabricated by ATZ, Germany.

Fig. 2 shows one of these pieces and signs the points where the superconductor was cut to obtain a bipolar circuit.

The aims for this configuration are based on previous works [13], [14] done with a smaller superconducting disk that was moved by the rotating magnetic field of a permanent magnet. Extrapolating the results of those works (Table I), we estimate that about 10 mNm can be obtained with a mean magnetic field of 120 mT on the new rotor (60 mT from each semistator in the configuration of Fig. 1). This magnetic field can be obtained...
Fig. 2. One of the coils to be used in the stator. The indicated cuts are filled with resin to stabilize the piece mechanically. The magnetic field has two poles as indicated.

TABLE I
DATA FROM PREVIOUS TEST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working temperature</td>
<td>77 K</td>
</tr>
<tr>
<td>Disk inner radius</td>
<td>1 mm</td>
</tr>
<tr>
<td>Disk outer radius</td>
<td>15 mm</td>
</tr>
<tr>
<td>Disk thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Number of poles</td>
<td>2</td>
</tr>
<tr>
<td>Mean magnetic field</td>
<td>2 mT</td>
</tr>
<tr>
<td>Pull-out torque</td>
<td>0.4 mNm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>0.9 mNm</td>
</tr>
</tbody>
</table>

TABLE II
EXPECTED DATA FOR 10 mTm TORQUE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working temperature</td>
<td>77 K</td>
</tr>
<tr>
<td>Disk inner radius</td>
<td>1 mm</td>
</tr>
<tr>
<td>Disk outer radius</td>
<td>25 mm</td>
</tr>
<tr>
<td>Disk thickness</td>
<td>5 mm</td>
</tr>
<tr>
<td>Number of poles</td>
<td>2</td>
</tr>
<tr>
<td>Mean magnetic field</td>
<td>120 mT</td>
</tr>
<tr>
<td>Pull-out torque</td>
<td>10 mNm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>To be found out</td>
</tr>
</tbody>
</table>

by a two-phase sinusoidal current system of about 1000 \( A_{\text{RMS}} \). Each coil would give 42 mT per-pole as indicated in Fig. 2, and the couple of coils \( \pi/2 \) rad out of phase in space carrying 1000 \( A_{\text{RMS}} \) \( \pi/2 \) rad out of phase in time would give a magnetic field of \( \sqrt{2} \times 42 \approx 60 \) mT. So we would obtain about 120 mT from the complete stator.

Table II summarizes the data of these estimations.

III. MAGNETIC FIELD MEASUREMENT LIMITS

The proposal of the present work was to design a procedure to know experimentally the magnetic field of a coil like that in Fig. 2 under the influence of the superconducting disk that have to be moved. A measured magnetic field of about 42 mT with 1000 A indicates that the desired torque can be reached.

But one of the more important handicaps that face the electrical applications of bulks is the difficulty to make an external current pass though them. The electrical connection between the ceramic material and a normal conductor (usually Cu, Ag, Al, ...) is always a hot point in the circuit that heats the superconductor up to the quench when the current increases up to values much smaller than those that the superconductor can support inside (transport capability of the material).

We have tried to improve the contacts between the coils and the current leads to get 1000 A, but the highest current without risk of quench that we have got was 60 A.

That situation made us establish again the test requirements to be now 60 A of current in the coil. Under the new condition, the magnetic field in each coil must be of about 2.5 mT.

Therefore, getting 2.5 mT with 60 A in the coil, we will get 42 with 1000 A and the rotor will give about 10 mNm as desired.

IV. EXPERIMENTAL

The experimental device used to measure the axial magnetic field component is shown in Figs. 3 and 4. It consists of a Hall probe that can be positioned in place by means of a Cartesian positioning system.

The coil is fed by a system that consists of:

- a voltage generator adjustable both in amplitude and frequency,
- a power amplifier
- a transformer that reduces the voltage and increases the current up to required level.

The frequency for these tests was 10 Hz that corresponds to a rotation speed of 600 rpm with two poles.
The movement of the probe is with steps of 1 mm along the $x$ and $y$ axis.

The probe covers a half of the surface of one of the poles, that is, a quarter of the coil. This is because the screw in the central hole of the pieces and the structure of the positioning system prevents the probe from passing.

V. RESULTS AND DISCUSSION

In order to describe as carefully as possible the behavior of the magnetic field, several tests under different conditions were carried out:

A. Measurement of the magnetic field axial component, $B_{ax}$, over (or below) a single coil.
B. Measurements of $B_{ax}$ on each side of the disk when it is placed under the coil, at its working position (Fig. 3), in ZFC conditions.
C. Measurement of $B_{ax}$ with the same arrangement as in paragraph B but in FC conditions.
D. Measurement of the trapped magnetic field on the disk magnetized in FC condition, after retired the coil.
E. Measurement of the peak values of $B_{ax}$ as in paragraph B under AC magnetization current.

The results and comments are as follows:

A. $B_{ax}$ Over the Coil

As known by previous works [15], the magnetic field created by one single coil like in Fig. 5 does not depend on the superconducting or normal material that it is made of.

Fig. 6 shows the results of this test. It can be observed that the maximum is of almost 3 mT and it is in the center of the pole, as expected.

B. $B_{ax}$ on the Sides of the Rotor Disk Under ZFC Conditions

In the second test (Fig. 7) the magnetic field is screened by the disk and concentrated near the current.

The measurements between the coil and the disk are shown in Fig. 8 and confirm such a concentration. So, it can be observed that the maximum values are not in the middle of the pole, and they are a little bit larger than in the previous test.

C. $B_{ax}$ on the Sides of the Rotor Disk Under FC Conditions

In FC conditions we expect the best behavior of the system working as a motor because the pulling forces in the disk are
mainly due to the trapped flux (at least in synchronous operation). Fig. 10 shows the planes where the measurements were done and the field lines, some of them crossing the disk.

The results of the test are in Figs. 11 and 12.

Between the coil and the disk one can see a magnetic field level close to the measurement in the same plane in ZFC conditions but the form is now less smooth than there due to the irregularities of the material.

Under the disk the result is different. Here the shape of the map is the typical shape of a trapped field map, and the amplitude of $B_{\text{ax}}$ is of about 1 mT (30% of the magnetic field between the coil and the disk). Under the influence of the complete stator, one expects a magnetic field trapped larger than 2.5 mT, enough for our proposal.

D. $B_{\text{ax}}$ Trapped in the Disk After Taking Out the Coil

The results are quite similar to those in Fig. 12. Irregularities in the shape remain after taking out the coil.

E. $B_{\text{ax}}$ Created by AC Magnetization Current

As we probed in our mentioned works [1], [2] the rotating trapped magnetic field pulls the disk at synchronous speed, against the external torque over the disk, until this torque is greater than a value called pull out torque. Then the vortices are depinned and can move in the material. In this case, the magnetic field varies with respect to the disk like with an alternate current in the coil if the disk is stopped. When the vortexes are free to move, they are repelled by themselves and migrate to the border of the material.

The test was done like in Fig. 13, similar to the test in Fig. 10 but 60 A peak AC current of was used. The magnetic field lines are similar too but inside the disk they are expected to move to the borders.

Fig. 14 shows the results that in this case are very dependent on the defects of the disk. The magnetic field in the middle of the pole is very low and near the borders increases very quickly but only in certain areas where the defects are located.

On the other side of the disk the magnetic field under the disk is very low (Fig. 15) but the main defects in the disk can be detected.

VI. CONCLUSIONS AND FURTHER WORKS

A description of the magnetic field in a superconducting complex system under different conditions has been reported.
In all the cases the magnetic field appears to be high enough to assume that 1000 A_{RMS} in the coil can make the motor rotate at synchronous speed against a torque of about 10 mNm.

Now a theoretical description of the pulling process is under study by our group. This description is based on the calculation of the vortex density in the disk and the associated forces described in [14].

REFERENCES


