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Iron-YBCO heterostructures and their application for trapped field superconducting motor

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Abstract. In this work we report on the magnetic behavior of the heterostructures formed by bulk based YBCO rings and ferromagnetic yoke. The magnetization cycle has been performed by an In-Field Hall Mapping technique. A video-like recording of the magnetization process makes it possible to obtain the magnetization of selected areas. The current flowing through the superconducting rings can be deduced from the magnetic field maps. The displacement of the peak of magnetization due to the flux reversal produced by the magnetization of the yoke is also considered. These hybrid heterostructures formed by ferromagnetic and superconducting material have been applied in the construction of the rotor for a brushless AC motor. The design and construction of this machine was carried out within the framework of the TMR Network SUPERMACHINES. The rotor has been designed in a quadrupolar configuration by cutting large YBCO "window frames" from seeded melt-textured single domain YBCO pellets. This rotor has been coupled to a conventional stator of copper coils wound on an iron armature. The stator can be excited both in bipolar or quadrupolar mode. We report on the behaviour of the motor after a field cooling process when excited in quadrupolar mode.

1. Introduction

The effectiveness of superconducting motors has been considered for the case of very large systems, where the gain in efficiency and size is obvious from the economic point of view. Fractional motors, however, can be an interesting field in specific applications, if the higher density of power and specific use is taken into account. No-bearing motors, cryogenic pumping and high specific torque could be a good example for such a kind of applications. [1,2,3]. Up to now, in the "low power-low size" range, two classes of motors have been developed, those working by the hysteretic behavior of SC bulks and those that use the very high reluctance anisotropy between superconducting diamagnetic and ferromagnetic paths, the so called reluctance motors. The capacity of the SC bulks to trap field has been suggested to improve the permanent magnet class of motors, but its effective magnetic flux density is strongly related to the size of the pellets. It means so that there are a critical threshold for the effectiveness of this kind of motors. Stability of the flux and the hysteretic behaviour of the magnetization are also properties that affect the long term working conditions of the motor.

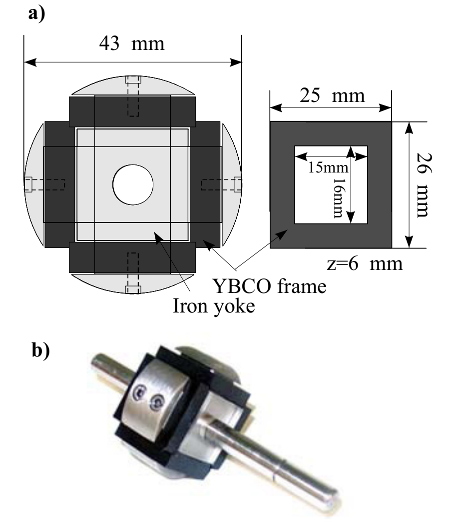

Figure 1. a) Schematics and dimensions of the of the hybrid YBCO-iron rotor; b) Assembled rotor.

In this paper, we consider the possibility to improve the density and the stability of the trapped flux in low size motors by using hybrid superconducting-iron rotors. In this case, the highly dense flux in the iron is blocked by using the screening effect of SC rings, so obtaining a permanent flux system capable of interacting with a conventional copper-iron armature. The development of this motor has been realized within the frame of the European TMR Network, SUPERMACHINES [4].

2. The motor

The motor has been constructed starting from a commercial induction motor, where the 43 mm squirrel cage rotor has been substituted by a hybrid iron-YBCO rotor shown in Figure 1. The armature is built up with laminated electrical steel with 16 independent copper coils wound over the corresponding slots. The armature allows several pole and phases configurations, with flexibility enough to excite the rotor in four phases-four pole configuration, 8 phases-two poles, or any other consisting of a power of two number phases, thus allowing several working configurations based in two poles or four poles according to the rotor geometry.

Magnetic measurements of the YBCO square rings of the rotor show that the remanent currents reach a value of 2500 A.

3. Magnetic behaviour of the blocked flux

In order to determine the magnetic effectiveness of the suggested hetero-structure, we have measured the magnetization cycle of the structure formed by a SC ring and an iron yoke. The characterization has been realized by using the In Field Hall Mapping technique, described elsewhere [5], which allows the determination of the local magnetic behaviour during a magnetization cycle. The measurements have been performed for the iron yoke, the SC ring and the combination of both. Figure 2 summarizes the results.

The ring behaves in the way we can expect for a superconductor. We observe, Figure 2 (i), that as the applied field increases, a magnetization of opposite sign develops; the squared symmetry of the magnetization profile corresponds to a shielding current running around the squared YBCO frame. Above the penetration field H^{*}~2500 G, the YBCO ring is not able to shield the applied field anymore and flux enters into the center of the ring. The applied magnetic field is brought to a maximum value 0.6 kG>2H^{*}. Then, as the applied field is decreased, shielding currents change sign and the magnetization is reversed, the inversion (M=0) occurring at 3800 G. The remanent magnetization at zero applied field is 1500 G.

The iron yoke, Figure 2 (ii), reproduces well the behaviour of the iron with a large demagnetization effect due to its shape. A cylindrical magnetization profile develops with the same sign as the applied field. Up to the maximum field that could be applied in our measuring set up, 6 kG, the iron magnetization response was linear, and the maximum trapped field was 1700 G.

The magnetic behavior of the YBCO+iron heterostructure is analyzed with the help of Figure 2(iii). Up to the YBCO ring penetration field, H^*~2500 G, the superconducting currents shield the iron core placed inside, and the magnetization observed is only owed to the YBCO (a-b). Above this field, flux entering the ring center is trapped into the iron core; the magnetization then has same sign as the applied field at the center, and opposite in the YBCO material (profiles c-d). The maximum magnetization occurs at a field (f), H ~1 kG, shifted from zero, such that the magnetization in the superconductor is zero. Note that, as desired, the maximum trapped magnetization 3400 G is much

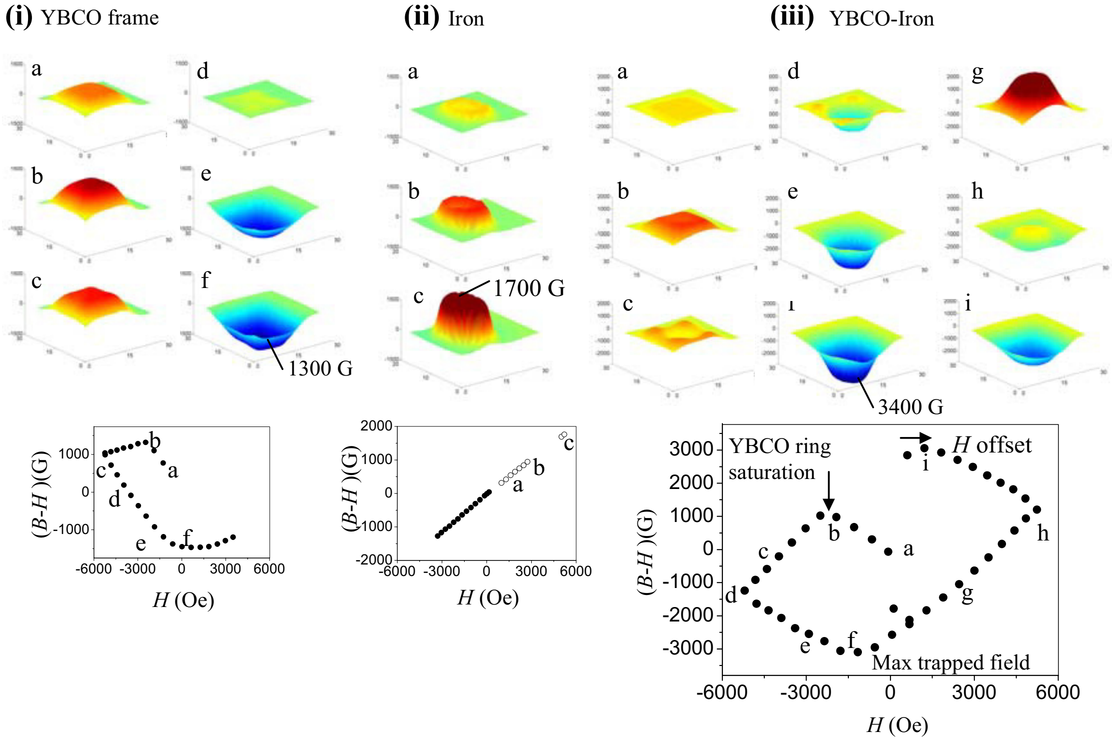

Figure 2 Magnetization process along a hysteresis cycle of an YBCO ring with a circular 8 mm centered hole and a rectangular 11x12x4 mm^3 external shape (i), an 8 mm cylindrical yoke (ii) and the heterostructure combination of both (iii). The graphics summarize the change of the mean value of the magnetic field B_z for each cycle as a function of the applied external field. Units of the maps are $B_z - H$, Gauss, x and y coordinates are expressed in scan steps (160 µm).

larger than the value that could be reached with the iron core alone or the superconducting ring thus indicating that the capacity to trap field is increased by using this kind of heterostructures.

4. Motor characterization measurements

In order to test the behaviour of the motor we have performed measurements of the static torque by energizing a set of four coils in a quadrupolar configuration.

The rotor has been, thus, magnetized by the excited coils of the stator along a Field Cooling process (FC). In order to avoid the excessive heating of the copper coils the armature has been pre-cooled up to a temperature estimated of 100 K, where the diminishing of the resistance allows increasing the exciting current. In figure 3 we show the resulting torque as a function of the load angle after cooling with an applied current of 15 A. The torque has been measured after 2 hours with the motors disconnected, by applying currents of 1 and 2 A. The torque shows a quasi linear behaviour for angles lesser than 20º and the slope depends on the interacting current. The changes of the field distribution due to the slots are well sensed by the torque curve which shows the steps by a sudden diminishing each 22.5º. The torque decay can reach negative values, not reflected in the curve because the measurement system requires equilibrium with positive forces only. The redistribution of the magnetic flux in each new tooth introduces changes in the slope, but the peak values tend to reproduce the sinusoidal shape as expected for a constant flux system. A sudden and negative high torque is observed after the 90º of load angle has been reached. The curves do not show any hysteresis thus indicating that no change in the flux blocked by the superconductor occurs. The flux remains stable after each measurement.

In figure 4, we summarize the initial (load angle smaller than 20º) slope of the torque curve for interacting currents up to 6 A, after field cooling the motor with a magnetizing current of 25 A.

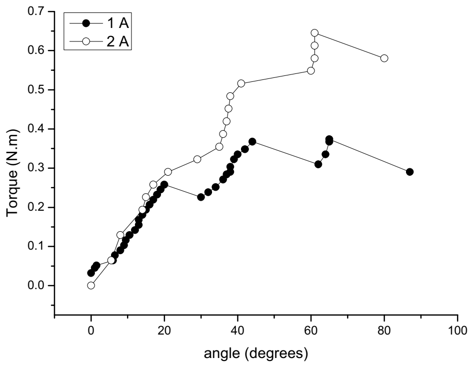

Figure 3- Static torque of the motor vs. Angle for different interacting currents after field cooling with a current of 15 A in a quadrupolar configuration.

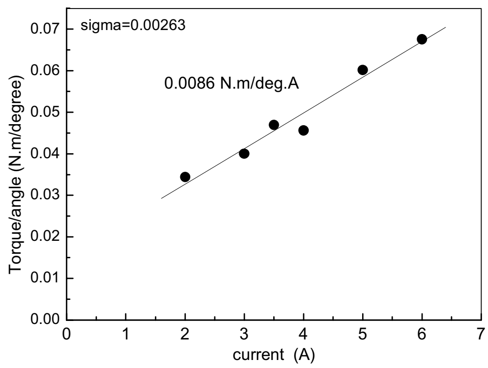

Figure 4- Slope of the static torque curve for low angles as a function of the applied interacting current after field cooling with a magnetizing current of 25 A.

After the FC process., the motor was disconnected and the torque was measured 2 h later. The slopes are higher than those obtained in the previous experiment, in coherence with a larger flux trapped in the rotor, and show a linear behaviour with no tendency to saturation. As in the experiment before, no hystersis is observed after large loads have been applied, thus indicating the effectiveness of the flux blocking by the SC rings. Although the maximum torque reached is 1.2 Nm, the behaviour of the motor suggests that the interacting current, now limited by the experimental setup, could be increased up to a new limit: the end of the non-linear regime, which corresponds to changes in the flux trapped in the rotor.

5. Conclusions

The limitation of the effectiveness of the trapped field superconducting machines, due to the dependence of the flux density with the size, could be overtaken by using a hybrid superconductor-iron heterostructure for the rotor, as has been tested. The architecture of YBCO frames blocking the flux in an iron yoke for the rotor introduce an enhancement of the field trapped in the iron core above its saturation field.

The hysteretic magnetic behavior of YBCO-iron heterostructure, studied by Hall probe magnetometry, has been discussed and a clear increase of the flux density is observed.

A motor designed on that basis has shown its feasibility and the stability of the trapped flux has been demonstrated in terms of its torque behavior, which does not show any hysteresis. The operation modes of the motor have been discussed.

A way to extend the application of superconducting elements to fractional motors seems to be opened.

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