Magnetisation of 2G Coils and Artificial Bulks

T.A. Coombs, J.F. Fagnard, K Matsuda

***Abstract*— The use of (Re)BCO is limited by the problems of magnetisation / demagnetisation. (Re)BCO is available in many forms but two of the most interesting for high magnetic field applications are 2G tape and Bulks (either or as grown or manufactured artificially using 2G tapes). The minimum joint resistance which can be achieved between YBCO tapes is of the order of 100 nΩ but this is still too large to operate coils in persistent mode. Bulks have potential to act as very high field magnets but in order to do this they need to be magnetised. This paper describes flux pumping methods which can be used to charge either coils or bulks.**

***Index Terms*—HTS, racetrack, YBCO, magnetisation**

I. INTRODUCTION

YBCO has been available, in various forms, since shortly after the initial discovery of high temperature superconductors by Bednorz and Mueller. All forms of YBCO have undergone large amounts of development since its first discovery and there is now a family of compounds which have been formed by substituting the Yttrium with other rare earths these are collectively known (RE)BCO. The largest field ever achieved using a YBCO bulk was 17.24 T which was reported in a 2.65 cm diameter sample at 29K in 2003 by Tomita & Murakami[1], before that in 2000 Fuchs et al achieved greater than 14T[2]. 2G tapes started to appear around 2001 and their properties have consistently improved year on year such that critical currents of 6-800 Amps/cm width in self field at 77K are routinely quoted by a number of manufacturers[3].

Even though the properties of these materials are potentially extremely useful and far exceed those available from conventional materials such as copper (wires) or NdFeB (magnetic field) there remain relatively few industrial applications and the barriers to widespread adoption remain high. Devices such as Fault Current Limiters, cables and transformers are becoming more widespread as the cost of the conductors gradually reduces over time but applications which use the magnetic properties are relatively few and far between.

There are two reasons for this; First the relatively high joint resistance means that running coils in persistent mode is not feasible and thus the obvious step for MRI of replacing Low Tc coils with High Tc ones has not been taken and to date no major manufacturer has plans to do it. The second reason is the magnetisation of bulks or artificial bulks. Consideration of the critical state model leads one to the conclusion that a bulk can only be magnetised using a source of magnetic field is greater than or at the least the same as the final desired field. However coupling the critical state model with an *E-J* law, and thereby including the effects of losses together with applying a travelling wave magnetic field [4,5,6] shows that this conclusion is incorrect. This technique can be used to magnetise superconductors in any form and this paper will show that the same technique can be applied to coils. Thus providing a means to recharge them and allowing them to be run in persistent mode..

II. DISCUSSION

A. Preparation of the manuscript

It is well known by Faradays law (1) that a changing magnetic flux induces an Electric field. This Electric field then leads to a current which opposes the change in magnetic field.

$$\oint_c E.dl = \oint_S \dot{B}.dS \tag{1}$$

Thus, if a magnet is drawn across a wire, the rising magnetic field as the magnet approaches the wire induces a current in the wire in one direction. Then, as the magnet passes the wire, the falling magnetic field induces a current in the opposite direction. This leads to an Alternating Current and is a fundamental basis behind the generation of AC power. If the wire is superconducting, though, something slightly different happens. The first is that, unlike a copper wire, where (within limits) the current is directly proportional to the total voltage from Ohm's law (V=IR) . In a superconductor the electric field and the current depends on the following relationship.

$$E = sign(J)E_0 abs\left(\frac{J}{J_c}\right)^n \tag{2}$$

where E_0 is typically 1μV/cm and J_c is the critical current or the current at $E= E_0$. Thus, the current no longer depends linearly on either the electric field and or by extension the rate of change of magnetic flux. Further the instantaneous resistivity is no longer linear. This is in turn means that magnetisation (and demagnetisation) are rate and magnitude dependent and not just magnitude dependent as is assumed in the Bean or Critical State model. This effect can be leveraged to produce a progressive magnetisation of the superconductor.

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T.A. Coombs is Cambridge University, Cambridge UK e-mail: tac1000@cam.ac.uk
J.F. Fagnard is with the Department of Electrical Engineering and Computer Science, Montefiore Institute, B28, University of Liege, Grande Traverse, 10, B-4000 Liege, Belgium. e-mail: fagnard@montefiore.ulg.ac.be
K. Matsuda is with Magnifye Ltd, 66 Maids Causeway, Cambridge CB5 8DD e-mail: km554@cam.ac.uk.

II. EXPERIMENT

We have reported on the magnetisation of bulks before [4,5,6] but to further test the hypothesis above we created a simple experiment fig. 1 in which a pair of magnets mounted on a shaft were spun above a 46mm wide superconducting tape which was used to short a superconducting coil. The motion of the magnets created a travelling magnetic wave, passing over the superconducting tape.

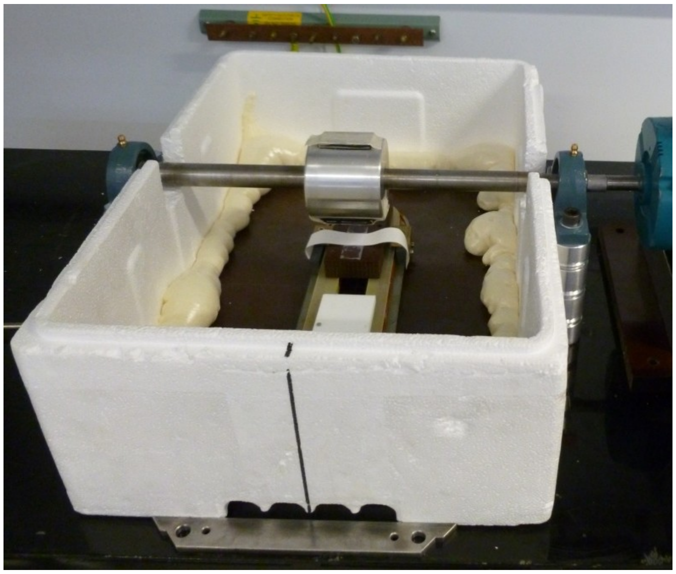

Figure 1: Basic experimental arrangement.

The coil was made from Superpower 4mm wide tape and the 46 mm wide tape was supplied by American Superconductor. Magnetisation was measured using a Hall probe placed in the plane of the coil at its geometric centre. The results below are given in terms of induced current in the coil which was calculated from the induced magnetic field.

Several experiments were carried out using this arrangement.

Experiment 1: - Superconducting coil shorted by a normal conductor followed by a superconducting conductor.

The container was first filled with sufficient liquid nitrogen to fully immerse the coil but insufficient to cover the 46mm tape which is shorting the coil. Thus the coil was superconducting but the short was not.

The magnets were then spun and nitrogen was gradually added until the 46 mm wide tape was fully immersed and became superconducting.

This enabled us to compare the behaviour between an arrangement where the coil was shorted by a normal conductor (in this case the nickel alloy substrate of the AMSC tape) and one where the short is superconducting.

The results are shown in figure 2. In this figure it can clearly be seen that when the tape is not superconducting an alternating current of magnitude less than one amp is generated. This is what would be expected from a simple consideration of Faraday's law. As the magnet approaches the wire the field rises producing an electric field and consequently a current. Once it has crossed the wire the field reduced producing a current in the opposite direction.

When the tape is superconducting an AC current is still observed but it is dwarfed by a DC current which grows over time as the coil is progressively magnetised. In this experiment the maximum induced DC current is of the order of 10 amps.

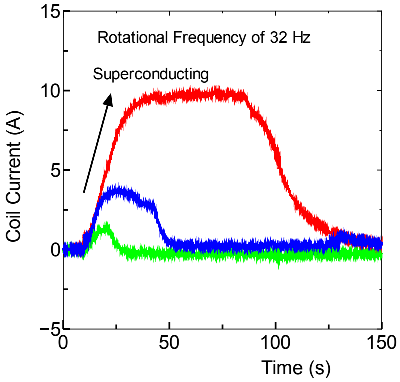

Figure 2 : Effect of having the superconducting coil shorted by a conducting/superconducting short.

Experiment 2: - Effect of speed and direction of travel of the magnetic wave

Having established that a DC magnetisation current can be generated with this arrangement a series of experiments were carried out at different rotational frequencies. In addition, for each frequency, readings were taken with the magnet's direction of rotation being both clockwise and anti-clockwise.

The peak current obtained was independent of rotation direction but varied with rotation speed. This enabled us to establish that the degree of magnetisation was rate dependent but not dependent on direction of sweep. Figure 3 shows the results obtained at two different rotational speeds and for rotation in both the clockwise and the anti-clockwise directions.

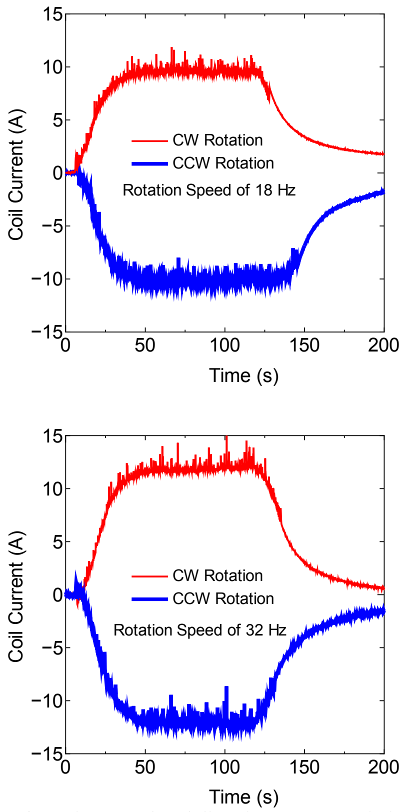

Figure 3: Effect of rotation speed and direction on magnetic induction.

Experiment 3 - The addition of a superconducting shield .

A type I flux pump flux, utilises a continuous ring of superconductor from which flux cannot escape once it has entered. In a type I flux pump the flux enters the circuit via a moving normal spot or a superconducting switch [7] In order to distinguish the mechanism from a type I flux pump a superconducting barrier composed of a stack of 24 superconducting tapes was placed along one edge of the 46 mm tape (fig 4). A Hall probe place below the shield was used to measure the effectiveness of the shield

With the shield in place magnetic flux is still drawn across the superconductor and induction can still take place. The purpose of the shield is to prevent the flux lines which pass through the superconductor from being dragged from one side to the other and thereby becoming trapped since, in order to do this, and in order to satisfy Gauss's Law (i.e. that flux lines are always closed) they would first have to pass through the barrier.

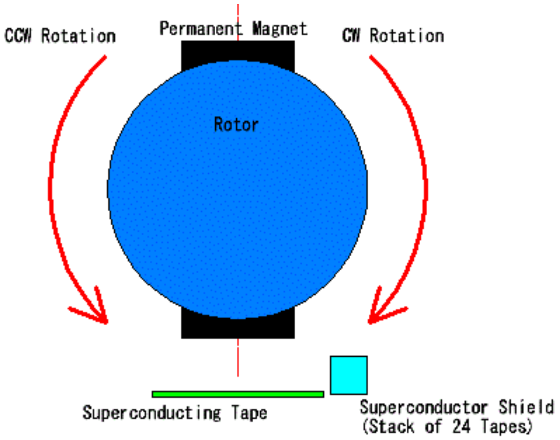

Figure 4: Experimental arrangement with superconducting shield.

The shield was not a perfect barrier but had the effect of partly shielding the field, from a peak of c. 0.1 T to c. 0.05T.

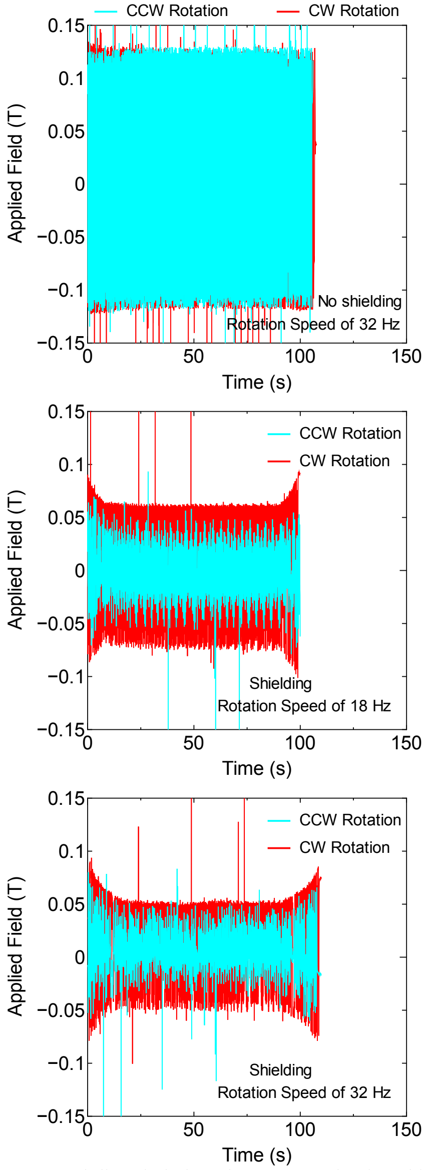

Figure 5: Flux measured directly below the superconducting shield.

The induction with and without the shielding was unchanged (figure 6) and hence the mechanism is not one in which flux is simply dragged into a magnetic circuit as would be the case with a type I flux pump.

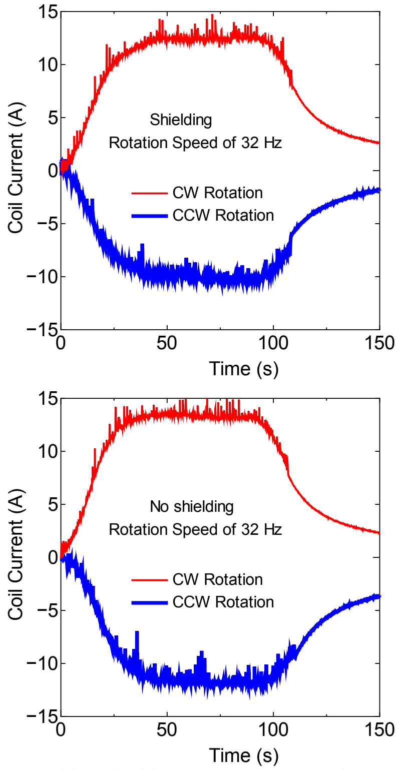

Figure 6: Induction with and without superconducting barrier.

Experiment 4 - Changing the total magnetic flux seen by the superconducting tape

This experiment involved investigating the effect of the total flux on the magnetic induction. Thus the rotor was displaced laterally in order to change the area of overlap and hence the total flux ϕ seen by the superconducting tape.

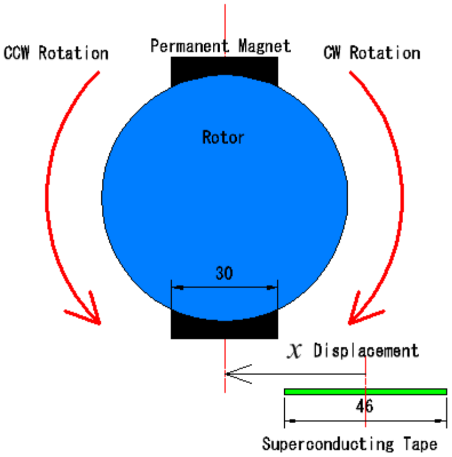

Figure 7: Experimental arrangement with rotor displaced laterally.

The results show that the magnetic induction varies with area of overlap as would be expected. They also further underline the premise that this is not a type I flux pump as the flux from the north pole at least is no longer being drawn across the entire width of the tape and cannot therefore be being drawn into the superconducting circuit.

Further to this the asymmetry which has been introduced can be seen in the fact that the clockwise and anti-clockwise rotation traces are mirror images of each other about x which is what one would expect.

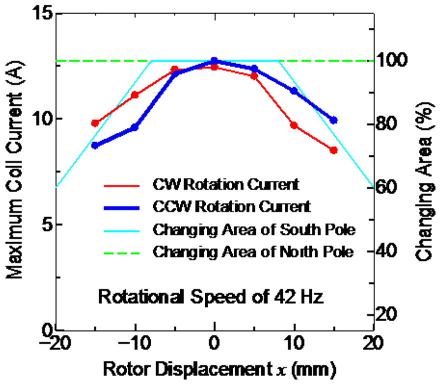

Figure 8: The induction varies according to the area of overlap of the magnetic poles.

Experiment 5- Addition of Iron to the Magnetic Circuit

Next we placed an iron plate underneath the superconductor. In this experiment we are checking whether the applied field is sufficient to fully penetrate the superconductor. If this were the case then the presence of the iron would increase the B field which the superconductor and would increased the induction accordingly.

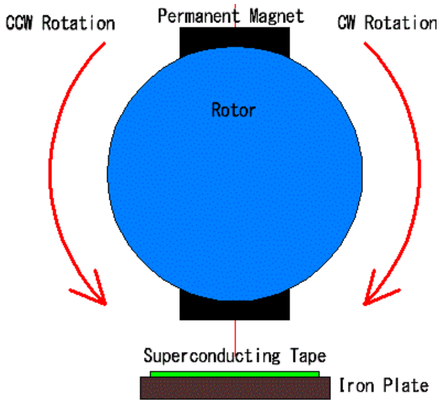

Figure 9: Experimental arrangement with additional iron plate of dimensions 52x52x6.4 mm.

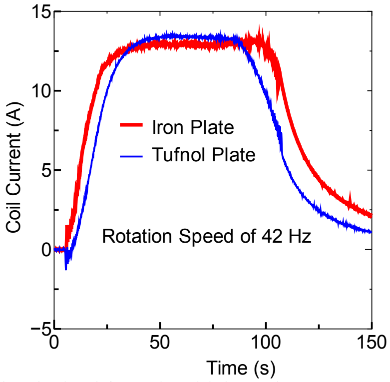

Figure 10: Results obtained from rig with iron plate.

Little or no difference in the induction is seen when the iron plate is present indicating again that it is not flux passing all the way through the superconducting tape (as would be required for a type I flux pump) which is producing the induction.

Experiment 6- Effect of changing the geometry of the superconducting shunt

In the final experiment we replaced the 46 mm wide American Superconductor tape with three 12 mm wide strips of Superpower tape (SF12100).

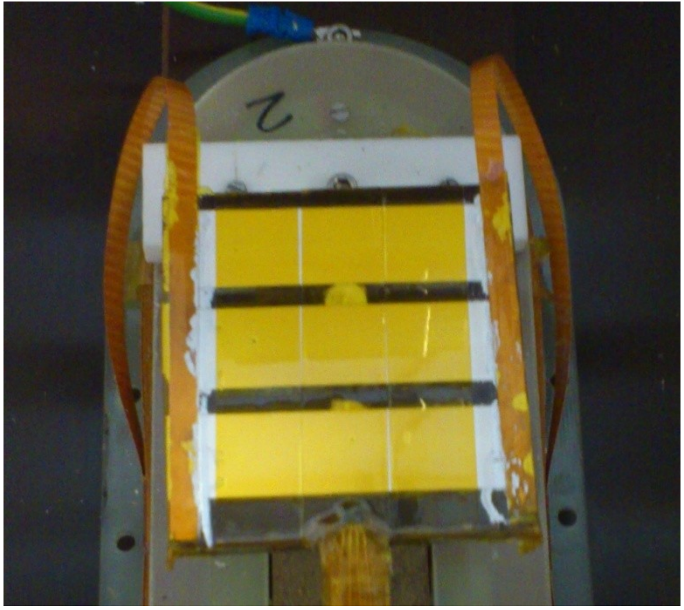

Figure 11: Coil shorted by three strips of Superpower 12 mm (SF12100) tape.

This had a dramatic effect and the final current reached was double the current obtained using the AMSC tape. The measured current was 25 amps which is close to the 32 amp critical current of the coil. This is predominantly due to the reduced joint resistance from three tapes in parallel as opposed to one single tape.

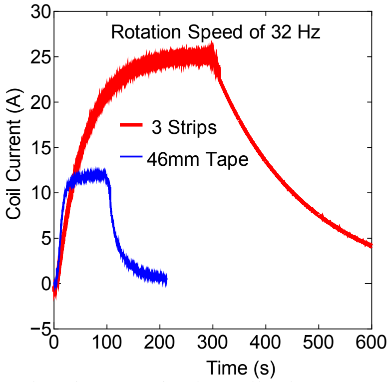

Figure 12: Comparison between shorting coil using AMSC 46 mm tape and three strips of Superpower's 12 mm tape.

III. MECHANISM

The experimental system as described above can be considered as consisting of three elements, the coil which is essentially a pure inductance, the interface between the AMSC wire and the coil which is a resistance and the flux pump itself which is acting as a voltage source.

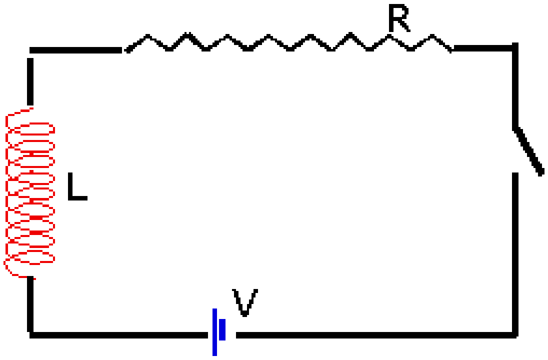

Figure 13: Simple Equivalent Circuit.

The governing equation for this system is:

$$V = L\frac{dI}{dt} + IR \tag{3}$$

Solving for the current we get.

$$I = I_{\max}\left(1 - e^{-\left(\frac{R}{L}\right)t}\right) \tag{4}$$

Using this simple model we can fit the results as shown in figure 14.

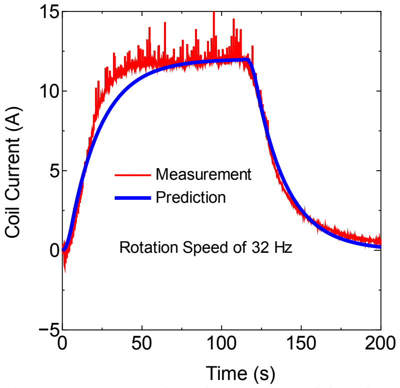

Figure 14: Comparison between model and experimental data.

IV. CONCLUSIONS

The crucial difference between flux passing over a superconductor and flux passing over a conductor lies in the fact that a superconductor has a non-linear *E-J* characteristic. This in turn leads to a non-linear resistivity. In a normal conductor where the frequency is low and therefore the skin depth is greater than the copper the resistivity is independent of either the magnitude of *B* or the rate of change of *B*. In a superconductor this is not the case. Even though Faraday's law still holds in a superconductor and the electric field is a direct function of $d\phi/dt$ the relationship between the electric field and the current is dependent on a power law with an exponent typically of the order of 20 or more. This leads to a rate of decay of the induced current which differs for different parts of the induction and ultimately leads to the offset DC current.

The technique we have described is as applicable to the magnetisation of bulks and artificial bulks as it is to coils.

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