

# Superconductors: The Next Generation of Permanent Magnets

T. A. Coombs, Z. Hong, Y. Yan, C. D. Rawlings

**Abstract**—Magnets made from bulk YBCO are as small and as compact as the rare earth magnets but potentially have magnetic flux densities orders of magnitude greater than those of the rare earths. In this paper a simple technique is proposed for magnetising the superconductors. This technique involves repeatedly applying a small magnetic field which gets trapped in the superconductor and thus builds up and up. Thus a very small magnetic field such as one available from a rare earth magnet can be used to create a very large magnetic field. This technique which is applied using no moving parts is implemented by generating a travelling magnetic wave which moves across the superconductor. As it travels across the superconductor it trails flux lines behind it which get caught inside the superconductor. With each successive wave more flux lines get caught and the field builds up and up. The wave could be generated in many different ways but the preferred way is simply to heat a material whose permeability changes with temperature at its edge. As the heat travels across the material so the permeability changes and a magnetic wave is generated. It is in effect the first novel heat pump in a very long time and one which will enable the enormous potential available from these unique and highly versatile superconducting magnets to be fully realised. Within this paper we present results showing the superconductor being progressively magnetised by sequentially applied “heat” pulses. We also demonstrate that the sign of the magnetisation is reversed if “cold” pulses are applied instead of heat pulses. These experimental results are supported by modelling.

**Index Terms**—Heat engine, Magnetization processes, Superconducting magnets.

## I. INTRODUCTION

Since the first discovery of high temperature superconductivity there has been a continuous improvement in the critical currents which the materials can support. Superconductors have been developed in thin-film, thick-film, bulk, wire and tape forms. There are many interesting and exciting applications for this technology. Before these applications can be developed certain technical problems have had to/ will be overcome. On the material's side much innovation has already occurred [1,2] and further success can be expected but already there is considerable scope for many interesting and exciting applications. At Cambridge we have worked on a number of these, including

fault current limiters, bearings and motors. Both fault current limiters and bearings are enabling technologies and a great deal of successful research has been devoted to these areas[4-8]. With motors, though, we are seeking to supplant an existing and mature technology. Therefore the advantages of superconductors have to be clearly defined before superconducting motors can become widely accepted.

The principle advantages of a superconducting motor or generator are size, weight and efficiency. Which of these is the most important depends on the application. In a wind turbine for example power to weight ratio is paramount. Any weight in the nacelle has to be supported and considerable savings can be made if the machine is lighter especially if it doesn't require the heavy unreliable gearbox a conventional generator requires. In a ship both volume and efficiency are important. For land based power generation connected to say a hydro-electric plant only efficiency is important.

Current designs tend to be synchronous machines in which the superconductor is on the rotor. In this configuration A.C. losses in the superconductor are kept to a minimum. As superconductors improve we are beginning to explore the possibilities of an all superconducting machine in which the A.C. losses on the stator are minimized by keeping the transport currents well below  $J_c$ . The ideal configuration will ultimately be a superconducting winding on the stator and a superconducting magnet on the rotor. The ideal material for the superconducting magnet would be superconducting bulks. This provides the most compact solution possible without the complication presented by creating a persistent current winding. The problem with using superconducting bulks is how to magnetise the bulks. This paper deals with the solution to that problem[10,11].

## II. THEORY

Current can be accumulated in a superconductor by creating a pulsed unidirectional electric field within it. If the electric field is small it will be initially excluded from the inner part of the superconductor by induced currents in its outer layer. However if the electric field is applied for a second time the outer regions will not be able to respond since they will already be carrying critical current. Thus current will be induced deeper within the superconductor to oppose the new electric field. By this mechanism the value of  $M0$  ( $M0$  is defined as the average magnetic moment over the volume due to the circling currents) will be increased by small amounts each time the electric field is applied.

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T. A. Coombs, Z. Hong, Y. Yan & C. D. Rawlings are with the EPEC Superconductivity Group, Cambridge University, Electrical Engineering Department, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, United Kingdom (phone: 44-1223-748315; fax: 44-1223-748348; e-mail: tac1000@cam.ac.uk).

This is different from the situation normally encountered when magnetising superconductors in which repeated application of a uniformly applied magnetic field does not result in a steadily increasing  $M_0$ . This is because a uniformly applied magnetic field will not generate the desired electric field pattern in the superconductor. As the magnetic field is increased from zero a positive electric field will be generated within the superconductor. However as the magnetic field is returned to zero an electric field will be generated in the opposite direction preventing a steady accumulation of current each cycle.

Hence by repeatedly applying a small magnetic field in such a way that the induced electric field in the superconductor always has the same sign a superconductor can be magnetised in steps. The final field magnitude can be greater than the magnetising field and is limited by the critical current and the geometry of the superconductor. It is not limited by the magnitude of the applied field.

It can be fairly straightforwardly demonstrated that a moving electric field accompanies a moving magnetic field. Starting from Faraday's law:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1)$$

Assuming that we have a magnetic field which is varying spatially in one dimension with time and which only has a component in the y direction we obtain:

$$\frac{\partial E_z}{\partial x} = -\frac{\partial B_y}{\partial t} \quad (2)$$

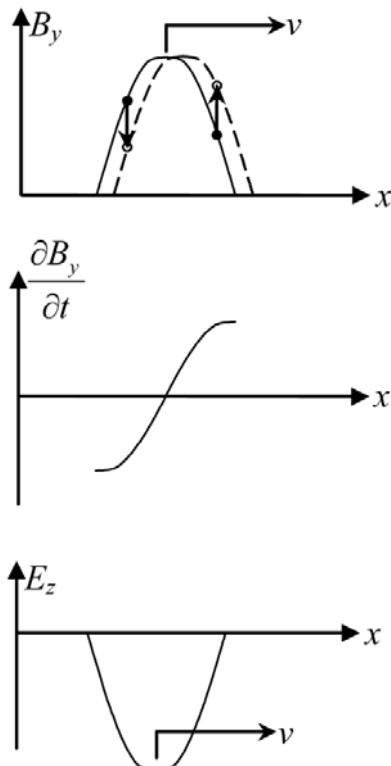


Fig. 1. Travelling magnetic wave together with associated traveling electric field

A graphical solution to this equation is given in fig. 1. In this figure we have a magnetic wave travelling in the x-

direction which generates a moving electric field according to equation 2.

It is clear from fig. 1 that the sign of the Electric field induced is dependent on the sign of  $\Delta B_y$ . Thus, successive waves of magnetic field will induce currents in the same sense and the magnetisation of the superconductor will be increased in steps. The sign of the resultant magnetisation of the superconductor  $\Delta M_0$  is dependent on the sign of  $\Delta B_y$  and the direction of travel. It is independent of the sign of  $B_y$  and so field can be induced in the superconductor which either reinforces or negates the magnetising field.

Thus sweeping a magnetic wave over the surface of the superconductor will progressively magnetise the superconductor. The form of the wave is arbitrary however it is clear that a pure sinusoid in which  $\Delta B_y$  is alternately positive and negative will not work since the current induced by one half of the sinusoid will be negated by those in the second half of the sinusoid. This will also apply to other symmetrical waveforms such as a square wave and may additionally apply to a waveform which can be expressed purely as the sum of sine waves.

A sinusoidally applied wave is akin to the classic Bean model in slab geometry where, when the field is first applied, currents of one sign are induced and when the field is removed, which is equivalent to applying a field of exactly the opposite sign, currents are induced in the opposite direction. After the first cycle unless the magnitude of the change is changed the magnetisation will follow a closed curve. Fig. 2 shows the classic bean model in slab geometry.

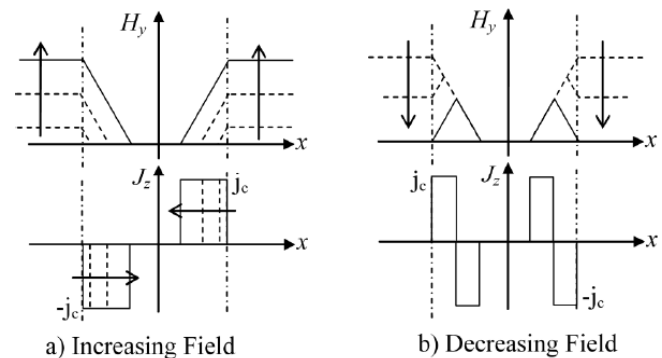


Fig. 2. Classic Bean model in slab geometry

Fig. 3 a) shows the MH curve for a superconducting slab in which the applied field has just fully penetrated the sample and then the field has been reduced to zero and increased again. Fig. 3 b) shows the current distribution in the superconductor as the field is cycled. In fig. 3b) only one quarter of the superconductor is shown. Both the x and the y axes are axes of symmetry.

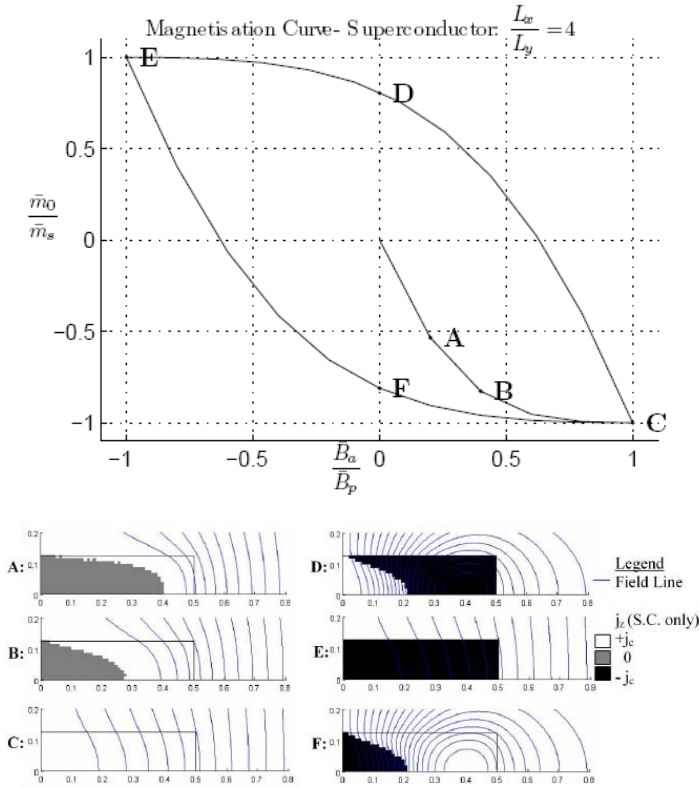


Fig. 3. Hysteresis loop and induced currents for a circular puck in a uniform applied field of cycled magnitude

No matter how many times the field is cycled, as long as the magnitudes of the applied fields are not changed the same hysteresis loop will be followed.

Causing a magnetic wave to move across a superconductor in the manner indicated fig. 1 however will pump more and more flux into the superconductor and this can be illustrated using the same model which produced the results given in fig. 3.

Fig. 4, shows the scheme for the model. The model consists of four elements, superconductor, air, temperature controlled ferromagnets and an iron magnetic circuit. The wave is simulated by switching the magnets on in sequence starting with the outermost magnets and moving in a steady progression to the central magnets.

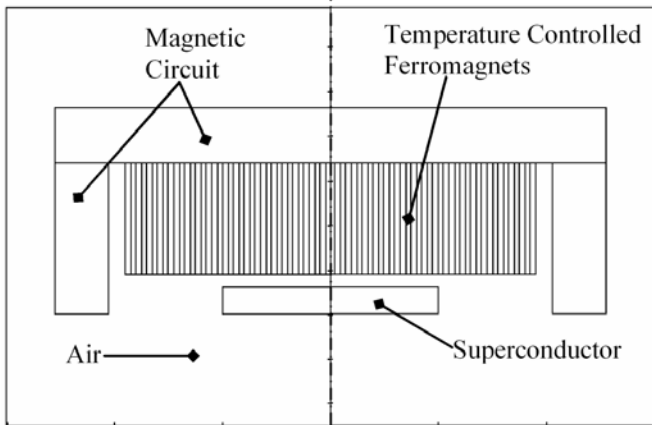


Fig. 4. Modelling scheme.

Fig. 5 illustrates how the current is built up in the superconductor as the magnetic wave travels across it. A

complete sweep is shown. At the end of the sweep a small amount of reverse current is induced as the wave collapses back down to zero.

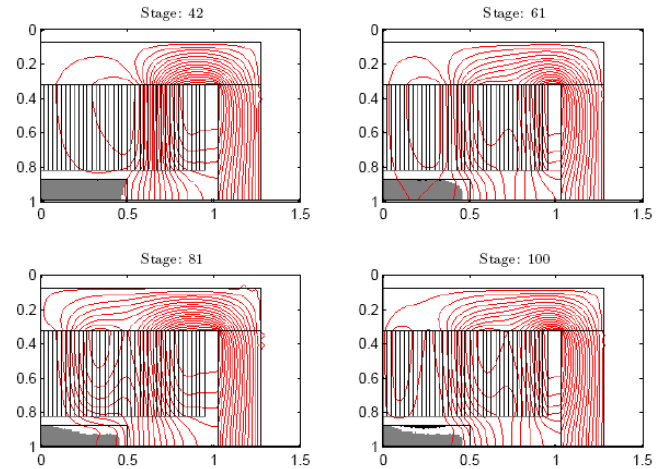


Fig. 5. Current induced during a single sweep

Fig. 6 shows how the magnetisation builds up as multiple sweeps are passed across the superconductor.

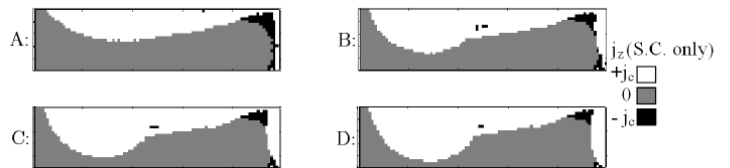
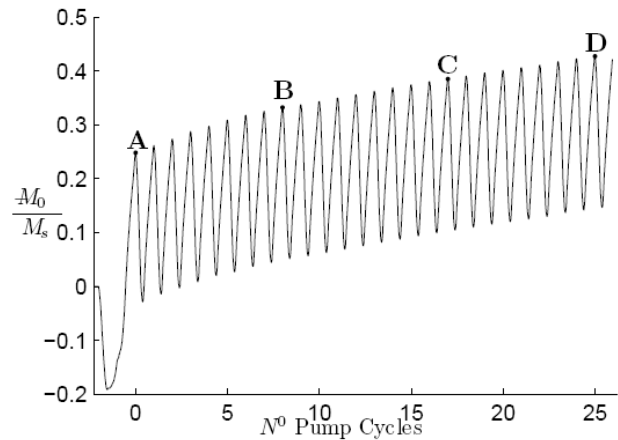


Fig. 6. Magnetisation and current distribution for multiple sweeps of magnetic field across the superconductor.

The current distribution at various points is also shown in fig. 6.

### III. EXPERIMENT

In addition to the models we have performed experimental measurements[9]. The most recent of these involved using gadolinium. The experimental arrangement is shown in fig. 7.

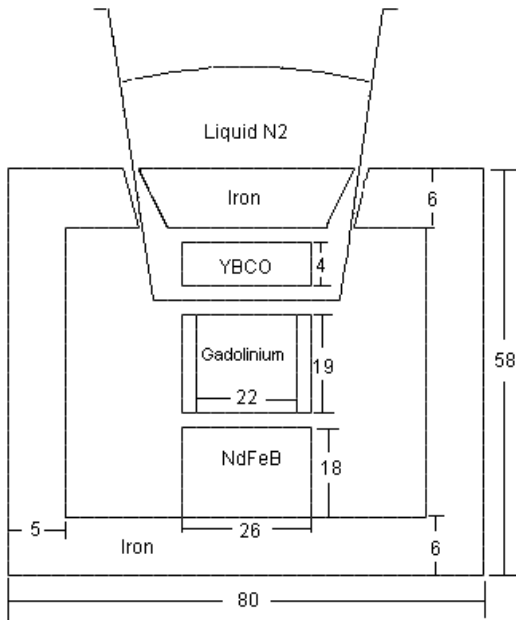


Fig. 7. Experimental arrangement (all dimensions are in mm).

Fig. 7 represents a circular iron can which forms a magnetic circuit around sections of YBCO and gadolinium. The YBCO is cooled with liquid nitrogen we have modelled how the field varies with the temperature of the Gadolinium. In the model at the start of each pass the gadolinium is at 0 °C. Heaters placed around the gadolinium are used to apply pulses of heat to the gadolinium. These pulses in turn produce magnetic waves which pass across the surface of the superconductor pumping flux into the superconductor. Fig. 8 shows a model of the temperature evolution and the subsequent variation in field at the middle of the superconductor.

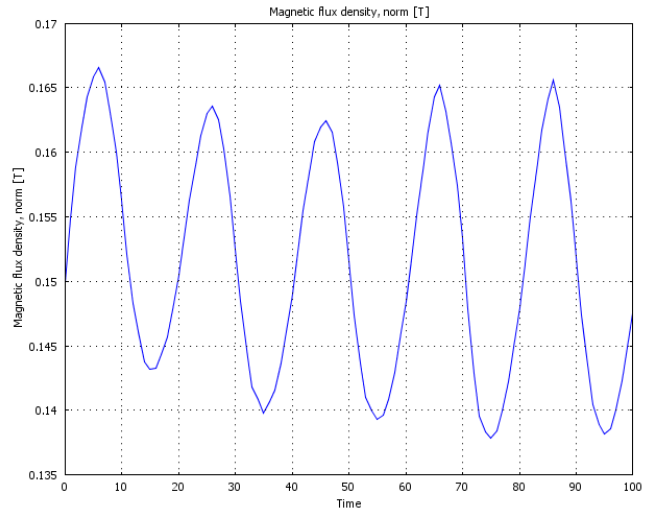


Fig. 8. Modelled variation of field as temperature of Gadolinium changes.

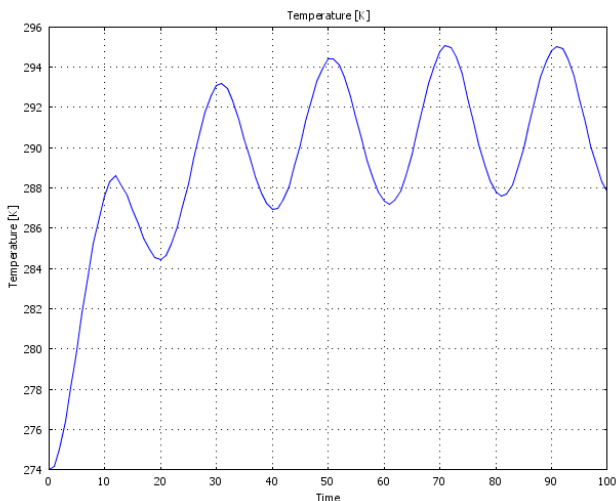
#### IV. RESULTS

Figs. 9 & 10 show a typical result obtained using the experimental rig described in fig. 7. In fig. 9 three traces are shown. The first trace where no superconductor is present shows the variation in applied field with temperature. In the second trace the sample of gadolinium has been gradually heated, and this situation corresponds to applying a single magnetic wave. In the final trace the heater has been switched on and off periodically. As the heater is switched the temperature rises in steps as can be seen from fig. 10.

In all three traces the effect of heating the Gadolinium is to bring it closer to its Curie point (23 °C). As this occurs the magnetic field applied to the superconductor is being progressively reduced.

In both the second and third traces the superconductor is being magnetised. This leads to the remarkable result in both traces that despite the applied field reducing the total overall field can be seen to be increasing. Thus the change in field due to the magnetisation of the superconductor is greater than the change in the applied field (this can be more clearly seen in fig. 10 which shows a close up view).

The importance of cycling can be seen by the fact that in the third trace where the heater is being switched on and off the superconductor ends up with a greater nett magnetisation than the second trace where heating is continuous and a single “wave” has been applied.



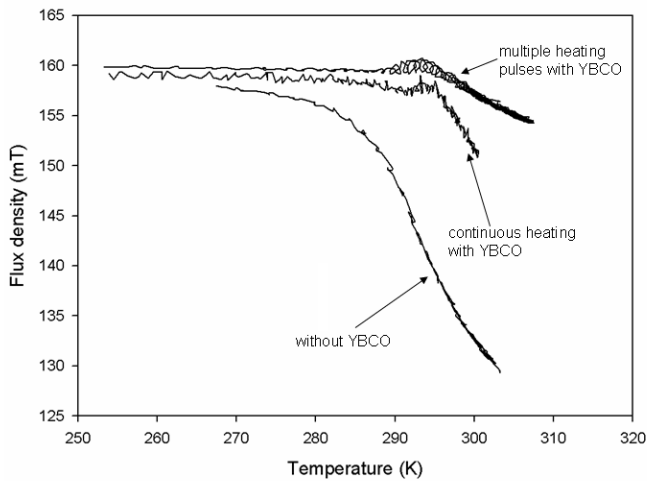


Fig. 9. Evolution of field with temperature – three traces are shown one where no YBCO is present, one where YBCO is present but the temperature is raised continuously and the third where the temperature is raised in steps.

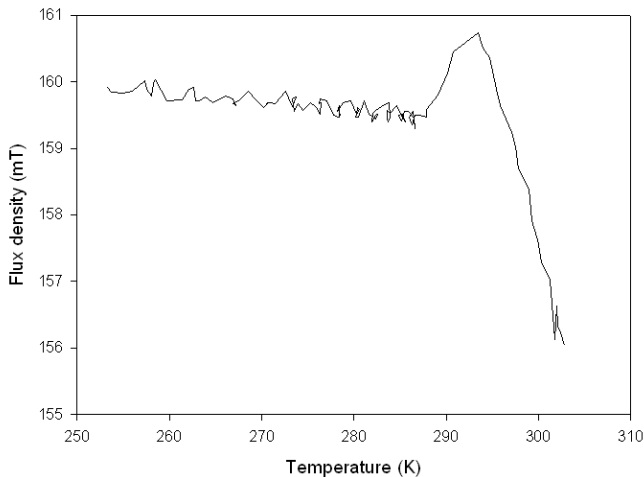


Fig. 10. Detail from fig. 9 showing multiple pumping cycles.

## V. CONCLUSION

The method of flux pumping presented in this paper is entirely novel. It differs from previous methods in several respects. The first and most important respect is that it exploits the unique characteristics of type II superconductors that current can be induced in the superconductor without destroying superconductivity. All previous methods as comprehensively described in [12] rely on locally driving the superconductor normal. The second respect is that the wave can be applied at any point on the surface of the superconductor thus different waves can be applied at different points. This means that the field from the superconductor can be shaped.

This paper presents a new modeling scheme which has been developed from the algorithm first presented in [3] together with experimental results derived from using Gadolinium as the active element. Gadolinium has been used here because it has a Curie point at approximately room temperature and potentially this simplifies the cryogenics. There are a range of materials which could be used including analogues of Prussian Blue[11] and Dysprosium which has a Curie point just above 77 K.

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