Numerical Analysis of Thermally Actuated Magnets for Magnetization of Superconductors

Quan Li, Yu Yan, Colin Rawlings and Tim Coombs
EPEC Superconductivity Group, Engineering Department, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK
ql229@cam.ac.uk

Abstract. Superconductors, such as YBCO bulks, have extremely high potential magnetic flux densities, comparing to rare earth magnets. Therefore, the magnetization of superconductors has attracted broad attention and contribution from both academic research and industry. In this paper, a novel technique is proposed to magnetize superconductors. Unusually, instead of using high magnetic fields and pulses, repeatedly magnetic waves with strength of as low as rare earth magnets are applied. These magnetic waves, generated by thermally controlling a Gadolinium (Gd) bulk with a rare earth magnet underneath, travel over the flat surface of a YBCO bulk and get trapped little by little. Thus, a very small magnetic field can be used to build up a very large magnetic field. In this paper, the modelling results of thermally actuated magnetic waves are presented showing how to transfer sequentially applied thermal pulses into magnetic waves. The experiment results of the magnetization of YBCO bulk are also presented to demonstrate how superconductors are progressively magnetized by small magnetic field

1. Introduction
Superconductivity was first discovered in 1911 by cooling mercury down to 4.2K [1]. Since then, continuous and tremendous research work has been carried out to improve characteristics of superconducting materials both electric-wise and magnet-wise, e.g. critical current and magnetization. Recent years, the research on high temperature superconductors (HTS) has been developing quickly, in order to reduce the energy consumption of cooling to critical temperature and, furthermore, to realize room temperature superconductors someday. Typically, a cooling power of 1W at 4.2K will demand the expenditure of some 500-1000W at room temperature [2]. As critical temperature rises up, the energy consumption of cooling decreases rapidly. The best know HTS are YBCO and BSCCO, which are both copper-oxide superconductors. The principle proposed in this paper is based upon the research on YBCO.

Superconductors can be applied to a broad area such as power storage devices, electric motors, magnetic levitation devices and etc, among which superconducting magnets, as some of the most powerful electromagnets, attract widely attention and hold large potential. Comparing to rear earth magnets, superconducting magnets are compact alike, while having magnetic flux density orders of magnitude greater. Superconducting magnets are capable to be applied in a lot of industrial and medical machines, such as superconducting generators/motors, Magnetic Resonance Imaging (MRI) devices and Nuclear Magnetic Resonance (NMR) devices. They can not only improve the performance of machines, but also reshape them as needs and reduce them in size. According to Bean model, which is being used most widely, twice as high as critical magnetic field $B_c$ is needed to achieve full magnetization/penetration[3]. In view of this, conventionally, extremely high magnetic fields or magnetic impulses are generated to magnetize superconducting bulks [4]. The devices used, which are usually solenoids, are big in size, very high cost and extremely high energy consumption.

In this paper, a Thermally Actuated Superconductor Magnetization System (TASMS) is presented to magnetize superconducting bulks. Unusually, not using high magnetic fields and impulses, TASMS
provides magnetic flux waves, with strength of as low as rare-earth magnets, travelling over the flat surface of a YBCO superconducting bulk to change its magnetization, shown in Figure 1. The travelling flux is activated by a Gadolinium (Gd) bulk, the magnetic permeability of which is visibly changed along with the transfer of thermal waves controlled by heating/cooling system.

Fig. 1 Travelling magnetic flux waves in TASMS

2. Thermal Control of Gd
Gd is a kind of magnetic permeability changeable (MPC) materials by adjusting temperature. It is strongly paramagnetic at room temperature, and exhibits ferromagnetic properties below room temperature. Figure 2 [5] shows that Gd changes from paramagnetic to ferromagnetic rapidly as temperature decreases around room temperature, while external magnetic field around is 0.4 T. This is the key property being used in TASMS to achieve changeable magnetic field wave along the surface of Gd bulk. As temperature decreases, Gd bulk changes from paramagnetic to ferromagnetic, vice versa, which makes it possible to control the strength of external magnetic fields by heating/cooling Gd bulk.

Fig. 2 Magnetization of a Gd single crystal

3. Magnetic waves
Figure 3 shows a model using heating/cooling on the edge of Gd bulk to generate desired travelling magnetic waves. Assuming the temperature on the edge changes sinusoidally and the faces are ideally insulated, the temperature on the edge is described as Equation 1.
The temperature diffusion equation is shown as Equation 2.

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t}$$  \hspace{1cm} (2)

where $\alpha = \frac{\lambda}{\rho c}$ is the thermal diffusivity and it depends on the conductivity $\lambda$, the density $\rho$ and the heat capacity $c$. Sensible non-dimensional groups for this problem are shown as Equation 3.

$$\bar{T} = \frac{T - T_0}{T_0}, \quad \bar{t} = \frac{\alpha t}{a^2}, \quad \bar{\omega} = \frac{\alpha}{\omega}$$  \hspace{1cm} (3)

Assuming a harmonic solution of $\bar{T} = \psi(x)e^{i\omega t}$ the diffusion equation for the problem becomes as Equation 4.

$$\nabla^2 \psi - j\bar{\omega} \psi = 0$$  \hspace{1cm} (4)

Equation 4 is solved for the edge heating model and the solution is presented as Equation 5.

$$\bar{T}(x, \bar{t}) = \Re \left[ \frac{\cosh\left(\sqrt{\bar{\omega}} e^{i\frac{\pi}{4}} x\right)}{\cosh\left(\frac{1}{2\sqrt{\bar{\omega}}} e^{i\frac{\pi}{4}}\right)} \right] e^{i\omega t}$$  \hspace{1cm} (5)

4. Modelling results

The TASMS model is shown as Figure 4, which is axis-symmetric. Heating coil is winded around Gd bulk and then the cooling water pipe. Table 1 shows the simulation reference.

| Subject       | Information                      |
|---------------|----------------------------------|
| Heating       | 50 kW/m²                         |
| Cooling       | Ice water, 273K                  |
| Gd bulk       | Diameter=22mm, Thickness=13mm   |
| YBCO bulk     | Diameter=22mm, Thickness=4mm    |
| Magnet bulk   | Diameter=26mm, Thickness=18mm   |
| Method        | Finite Element Method (FEM)      |
| Simulation Software | COMSOL Multiphysics V3.4    |

Heating coil and cooling water work in turn with a total period of 30 seconds. To enhance the transfer of thermal waves, a thin sheet of superconductive layer (copper in this case) is attached to the face of Gd bulk, only one side or both respectively. The thermal simulation result, which was tested at the central point of Gd bulk, is shown in Figure 5 and all the references are in Table 2. Apparently, thermal waves transfer faster with the help of superconductive layers. In this project, 1 layer case was selected and the magnetic simulation result, which was tested at the central point of YBCO bulk, is show in Figure 6. As designed, travelling magnetic waves are realized.
5. Experiment results

Based on the thermal model and magnetic model, experiments have been carried out to test the feasibility of magnetizing YBCO bulk using rare-earth magnets. The experiment results show that the Gd bulk can be controlled between 275K and 295K effectively, which activates magnetic flux waves changing from 0.4T to 0.7T. Under the waves above, the YBCO superconducting bulk can be gradually magnetized, as shown in Figure 7. The accumulation of magnetization attributes to flux creep, which makes magnetization and demagnetization uneven during each pump. By changing the flux creep of the superconducting bulk, it is obtained that the less the flux creep is the less pumps needed to achieve same magnetization.

From Figure 7, as temperature varies between 270 K and 290 K, the flux density of YBCO bulk increases from 117 mT to 122 mT and further. This case proofs that small amount repeating magnetic waves could magnetize superconductors and cause the accumulation of flux density.
6th Conclusion

This paper proposes a novel technique to magnetize superconductors. Conventionally, as described by Bean model, high magnetic fields or impulses should be involved. Unusually, this technique uses rare-earth magnets, which can be easily obtained. Thermal waves are actuated by controlling the temperature of Gd bulk, which, further more, generate magnetic waves travelling along the surface of YBCO bulk. As shown by simulation and experiment, YBCO bulk can be magnetized gradually by applying repeating travelling magnetic waves.

References

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