Superconductor Science and Technology

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To cite this article before publication: James Gawith *et al* 2019 *Supercond. Sci. Technol.* in press https://doi.org/10.1088/1361-6668/ab2d61

An HTS Power Switch using YBCO Thin Film Controlled by AC Magnetic Field

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Abstract— **This report is on the design of and results from a fast-acting, high power density high temperature superconducting switch. The switch uses thin films of $YBa_2Cu_3O_{7-x}$ on a sapphire substrate switched into the off-state through application of an AC magnetic field to the superconductor, which causes any transport current to experience a dynamic resistance. Results show reliable and repeatable switching of a 10x30 mm section of thin film between an on-state with Ic of 100 A and an off-state of 9 mΩ, with off-state voltage exceeding 100 mV. On-state to off-state transition time is less than 1 ms and off-state to on-state transition time is around 15 ms. These results are promising for further development of a high power, fast-acting superconducting power switching device for use in applications such as flux pumps.**

Index Terms—**HTS Switch, Thin Film, Flux pumps**

I. Introduction

Recently there has been interest in using Rare Earth Barium Copper Oxide (REBCO) High Temperature Superconductor (HTS) for applications requiring high magnetic field density including Nuclear Magnetic Resonance (NMR) [1], particle accelerators [2] and plasma confinement [3]. There is also interest where the high current density and low loss of these materials at practical temperatures can provide advantages over existing systems such as for superconducting electrical machines which can be made smaller and lighter for the same power and torque specification [4]. HTS has also found use in other specialist applications such as to limit fault currents in the power grid using the intrinsic electrothermal behavior of HTS material [5].

One of the main drawbacks in using superconducting magnets rather than permanent magnets is that superconductors require dedicated power supplies and additional components for cooling and magnetization. Charge, discharge and ensuring the safety of the magnet in the event of a quench often requires the use of superconducting switches. This paper looks at a switch designed to charge and discharge the magnet directly, using a superconducting rectifier or flux pump system.

Background is given about different superconducting switches and how they have been used. The physical mechanisms of the proposed switch are then presented, and limitations of previous designs are covered. A new candidate design using thin films is then presented and analyzed. The prototype and testbed for this new design are then detailed, and selected results are given. These results are discussed including how the switch could be improved in the future and conclusions are drawn about the suitability of this switch in real systems.

II. Background

In a traditional rectifier circuit, switches used are semiconductor-based devices such as the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) and Insulated-Gate Bipolar Transistor (IGBT). These devices provide a very high off-state resistance (≈ MΩs), have low on-state resistance (≈ mΩs) and have fast switching between states (≈ ns). In a superconducting system, the on-state resistance of these devices means that they cannot operate in persistent mode and so need a constantly operating power supply. At very high currents required by some systems, the on-state loss may become impractical. Flux pumps look to solve this issue by using superconducting switches. These switches are superconducting in the on-state and have a small, non-zero resistance in the off-state. This means they can handle very high currents with no loss for long time periods which is ideal for superconducting magnet systems.

The first application using superconductor as a switch was in computing, where it was demonstrated that an external magnetic field could control superconductivity and digital logic devices using this principle were made [6]. This idea was extended to using superconductor in power switching devices, initially also using magnetic field to control superconductivity [7]. At this time, the only known superconducting materials operated at very low temperatures (now known as Low Temperature Superconductors or LTS) and had low normal state resistivity, meaning any practical switches used large amounts of superconductor to develop a high off-state resistance.

With the discovery of HTS, which can operate at higher temperatures and has higher off-state resistivity, there have been several different avenues of research to develop switches including through optical [8], magnetic [9], pulsed/over current [10] and thermal mechanisms. These fundamental mechanisms were presented soon after the discovery of HTS and applications of these fundamental mechanisms have progressed in the subsequent years.

One of the most promising applications is for using over-current switched HTS as a limiting impedance in power grids systems in the event of a fault. Commonly referred to as Superconducting Fault Current Limiters (SFCL) these devices operate in the superconducting state under normal operation, but in the event of a fault current their critical current is exceeded, so they heat up above their critical temperature and present an impedance to limit the fault current and protect other grid equipment in the short time before circuit breakers are opened. With the advent of HTS, most SFCL are being designed to operate in nitrogen at 77 K [5]. SFCL can be thought of as automatic switching elements that operate the vast majority of their time in the on-state carrying large currents at low loss but also need to present a significant, reliable, fast acting impedance in the event of a fault.

Another application of superconductor switches is the Persistent Current Switch (PCS) which is used in superconducting magnet systems for magnetization and operating magnets in persistent current mode without the need of a power supply [11]. Long confined to LTS systems, in recent years efforts have been made to design HTS systems which can operate in persistent mode. HTS PCS [12] and HTS persistent mode joints [13] are the two crucial technologies to achieve this.

The focus of this work is developing an HTS switch for a Transformer-Rectifier Flux Pump (TRFP). A TRFP can be considered as a switch mode power supply (SMPS) employing superconducting switches. Early TRFP used thermally or magnetically switched LTS material with systems being made operating in excess of 10kA [14] and operated reliably in real applications. HTS flux pumping systems have gained a lot of attention in recent years with new thermally actuated flux pumps [15], rotating permanent magnet flux pumps [16] and TRFP [17].

Coombs and Geng [18] recently proposed a TRFP which uses an HTS switch which is switched into the off-state using an applied AC field to induce a dynamic resistance. This has the advantage of not having to thermally quench the superconductor, increasing the switch efficiency and reducing switching times. Importantly, decreased switching times means that flux pumps using HTS can operate at high frequencies and decreases the overall volume of the power supply. These AC field switches used commercially available second generation HTS REBCO coated conductors switched into the off-state by an AC field at low frequencies generated using electromagnets made from iron cores. The work in this paper looks at how the performance of such switches can be improved using different forms of superconductor and different electromagnets.

III. Existing AC Field Switches

The mechanism for the AC field switches was originally identified by Andrianov et al [19], who showed that a type II superconductor carrying a DC transport current will generate a DC voltage when a perpendicular AC magnetic field is applied to it. This analysis was extended by Jiang et al [20], giving the following equation for dynamic resistance:

$$R_{d\perp} = \frac{4aLf}{I_{c0}}\left(B_{a,\perp} - B_{th,\perp}\right) \text{ for } B_{a,\perp} >> B_{th\perp} \quad (1)$$

where a is the half width of the slab, L is the length of the slab subjected to the field, f is the field frequency, I_{C0} is the critical current of the slab, $B_{a,\perp}$ is the magnitude of the field applied perpendicular to the tape, and $B_{th,\perp}$ is the threshold field given in Jiang *et al* [20].

Seen from equation (1), to develop a higher resistance, the frequency or field strength can be increased. In theory, a high resistance per unit length could be achieved at high field or frequency. The resistance per unit length in the off-state is a very important metric as it determines the electric field achievable across the switch and therefore heavily influences the amount of conductor used, the volume of the switch and, to a large extent, its cost. However, there are practical limitations which have restricted resistance per unit length to low values previously [21], when using coated conductors.

An example of a coated conductor, SuperPower's SCS4050 [22], is seen in figure (1). In addition to the REBCO layer, there is also a substrate layer, buffer layers, a silver overlay and a stabilizer layer. Some of these other layers have low resistivity at 77 K and play an important role in limiting the maximum effective off-state resistance and therefore limiting the performance of the switch.

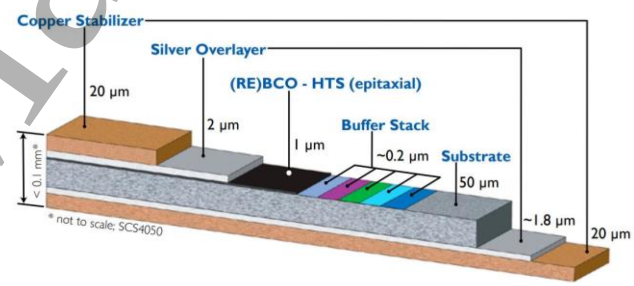

Figure 1. Diagram of coated conductor structure and layer composition [22].

Table (1) shows the resistance of the different layers per unit length. The material resistivity values are taken from literature [23] [24] [25] and the dynamic resistance values calculated from equation (1). This illustrates how coated conductors stabilized with copper offer a very poor choice of material for a switching element due to their very low normal state resistivity. Even coated conductors that are stabilizer free are significantly limited by the silver layer and to a lesser degree by the substrate.

Table 1. Resistance of Layers in an HTS Coated Conductor

Layer	Resistance per meter (Ω)
40μm Copper Stabilizer at 77 K	0.015
3.8 μm Ag layer at 77 K	0.3
50 μm Hastelloy at 77 K	7.5
Dynamic Resistance of YBCO layer at 100 mT, 1 kHz	1.5

Dynamic resistance of YBCO layer at 100 mT, 10 kHz	15
1 μm YBCO Thin Film at 100 K*	120

*YBCO-123 thin-film 100 K resistivity is used to show the 'normal state' resistance of these thin films. This is much higher than any target dynamic resistance.

IV. Design of an Improved AC Field Switch

It was identified by the authors that, rather than using HTS coated conductors for switches, thin films of HTS on insulating material could be used. This type of thin film has been used before in switches [8] [26] and in SFCL [27] [28], but not using the mechanism of dynamic resistance to switch between off and on-state. The main advantage of using thin films compared to coated conductors is that the only conductive layer present is the superconducting layer. This removes any parallel conduction path which increases off-state resistance and removes a source of loss compared to coated conductor switches. While these thin films seem like the clear candidate for an HTS power switch, it is useful to understand the limits of operation of such a device.

There has been much previous work on the electrothermal properties of thin films of YBCO on sapphire for use as SFCLs. This work included results showing that thin films can withstand very high powers (>2.5 $kVAcm^{-2}$), at least for short time periods (30 us) without damage [28]. One of the features of using sapphire as the substrate material is that at cryogenic temperatures, it has a very high thermal conductivity, around 1000 W/(m.K) [29], greater than that of high-purity copper, meaning that loss in the YBCO is directly sunk into the stabilizer, protecting it from overheating to some degree. However, the heat produced during operation eventually leads to a thermal limitation, with the YBCO rising above its transition temperature. It is important to analyze under what conditions this happens to ensure that the switch is operated in a safe mode.

There are two sources of loss for a superconductor in an AC field carrying a transport current: dynamic resistance loss and magnetization loss [11]. The dynamic resistance loss per unit volume per cycle is given as:

$$Q_b = \frac{B_m^2}{2\mu_0}\frac{2i^2}{\beta} \tag{2}$$

and magnetization loss per unit volume due to the external field is given as:

$$Q_f = \frac{B_m^2}{2\mu_0}\frac{1-i^2}{\beta} \tag{3}$$

where B_m is the applied magnetic field strength, i is the ratio of the transport current to the critical current, β is the ratio between the applied field and the threshold field and μ_0 is the permeability of free space. These equations show that the losses depend heavily on the ratio of the transport current to the critical current with the dynamic loss increasing with increasing transport current and the magnetization loss reducing with increasing current. This makes sense as once the transport current fills the superconductor, the applied field does not magnetize the superconductor which is already full of current – rather, the DC source experiences an AC resistance.

With a known power load calculated from equations (2) and (3) we have run simulations in COMSOL to evaluate the predicted thermal limits of operation of the device. High but realistic values of 200 mT at 10 kHz applied field give a power loss of approximately 200 mW per cm of thin film. Using this value as a baseline, figure (2) shows the temperature vs time predicted for a thin film of 330 nm of YBCO on 500 μm of sapphire exposed to a 50% duty cycle, 1 Hz heat load of 200 mW, cooled in nucleate-boiling liquid nitrogen [30].

Results show acceptable performance with the YBCO temperature staying well below its 90 K transition temperature. For comparison, to demonstrate the limit of operation of the device, we have also included predictions of a 2 W power load. This shows that if power loss were to increase, or if cooling channels are non-ideal, the maximum temperature increases above T_C. This would send the superconductor normal for part of the switching cycle and mean there is a long transition time between the on-state and off-state. This effectively limits the frequency of operation of the device and is a problem seen with previous AC field switches using coated conductor [21]. Testing these switches, we were conscious to avoid heating the films above T_C because, as well as increasing switching times, it could result in high thermal transients and damage the films.

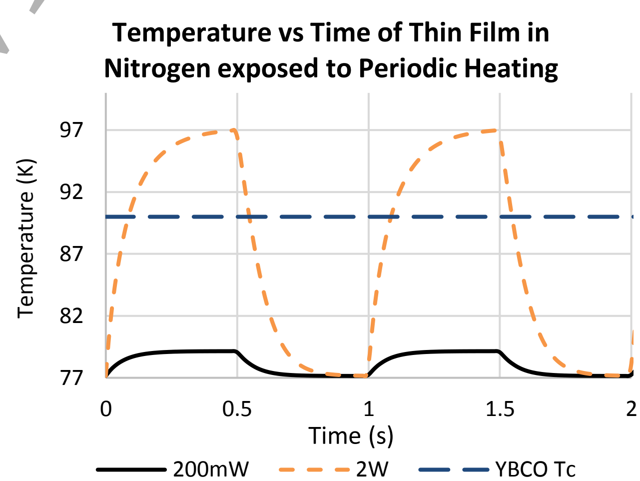

Figure 2. Results from a COMSOL heat transfer simulation of a thin film of YBCO on sapphire exposed to periodic heating in pool boiling liquid nitrogen.

V. HTS Thin Film Switch Prototype

The prototype switch tested uses a 10x60 mm section of YBCO thin film provided by Ceraco GmbH [31]. The film has 330 nm of YBCO deposited on a 500 μm sapphire substrate and 10 mm at either end have a thin Au coating onto which leads are soldered. The YBCO section in the middle is coated with silicon dioxide to protect it from degradation. With a critical current density of around 3.3 $MAcm^{-2}$ these films have a critical current of around 100 A at 77 K in self-field.

The electromagnets producing the AC field are made from FeSi powder cores from Micrometals [32]. These cores have a high saturation flux density and low core loss below about 100 kHz. The cores have 4 mm slots cut in them by waterjet and are wound with 1mm copper wire. The result is an electromagnet with an inductance of around 5 mH that can produce a field strength up to 200 mT RMS in a 4 mm gap to a 30 mm long section in the center of the film. At higher frequency, the impedance of the electromagnet becomes too high for the power supply to drive directly. High voltage film capacitors are used to compensate the inductance and drive the electromagnet resonantly from the supply.

A basic diagram in figure (3) shows the setup and instruments used for testing the switch. An EP4000 audio amplifier is used to drive the electromagnet and has a maximum frequency of 20 kHz and maximum power of 4 kW. A 62000P DC current supply drives transport current through the film. It operates in voltage limited mode with the voltage limit set such that the current limits at just over 80 A and is reduced when the film develops a resistance. It was important to get the voltage and current limits as well as the slew rate limits setup correctly to avoid driving too much power into the switch. The electromagnet is driven by an EP4000 power amplifier and is tuned resonantly with film capacitors for higher frequency tests.

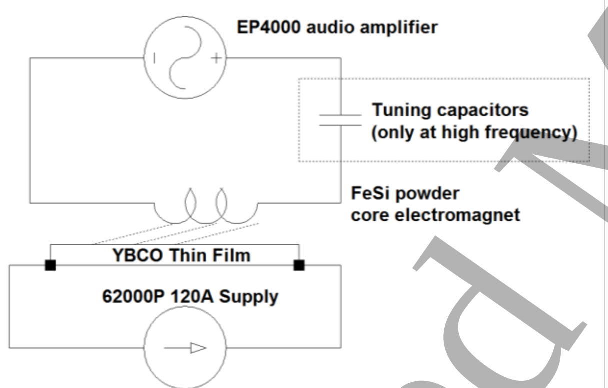

Figure 3: A basic diagram showing the hardware and configuration of the prototype test.

VI. Results

Initial results from the switch at low frequency, seen in figure (4), show an applied field of 120mT peak at 100Hz introduces a fast acting, controllable resistance, consistent with equation (1). The DC power supply is operating in voltage limited mode so when the field is applied and the film impedance increase, the current from the supply reduces. The results in figure (4) show the current is reduced to around 65A from its initial value of around 80A and produces an average voltage of about 30mV, giving a dynamic resistance of about 0.5mΩ. Both the switch-off and switch-on transients are only limited only by the rate of change of the applied field.

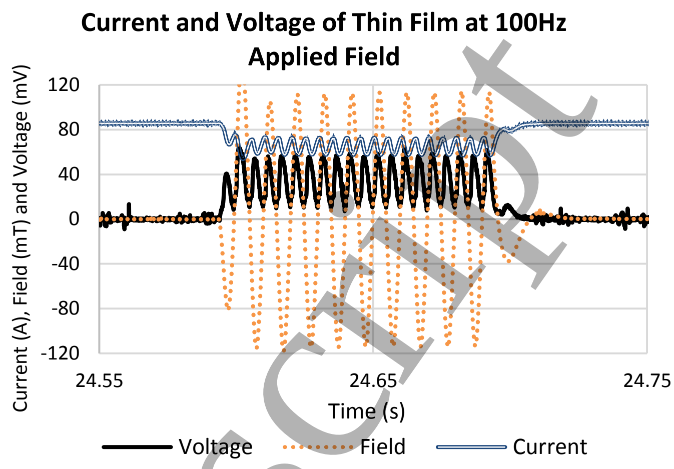

Figure 4: Result from applied field at 100Hz and around 120mT field strength.

Results at higher frequency, seen in figure (5), show that a 50mT peak field at 8.8kHz gives an average voltage of 116mV which limits the supply current to 13A for a dynamic resistance of 9mΩ. The initial voltage across the tape is high (>200mV peak) as the current from the power supply has not yet limited.

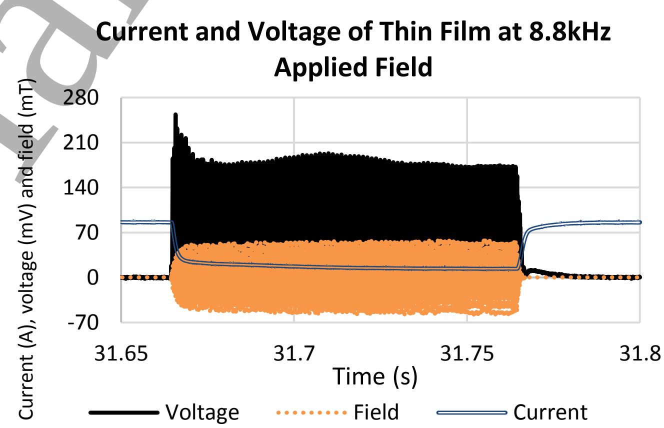

Figure 5: Result from applied field at 8.8kHz and around 50mT field strength.

The switch-off time (superconducting to resistive transition) is less than 1ms and depends on the time constant of electromagnet. During switch-on (resistive to superconducting transition) there is a short time for recovery of around 15ms which is shown in more detail in figure (6). This recovery time is thought to be primarily due to the inductance of the sample, but could have a thermal component. The physics behind this transition time and methods of reducing it will be an area of investigation for future work.

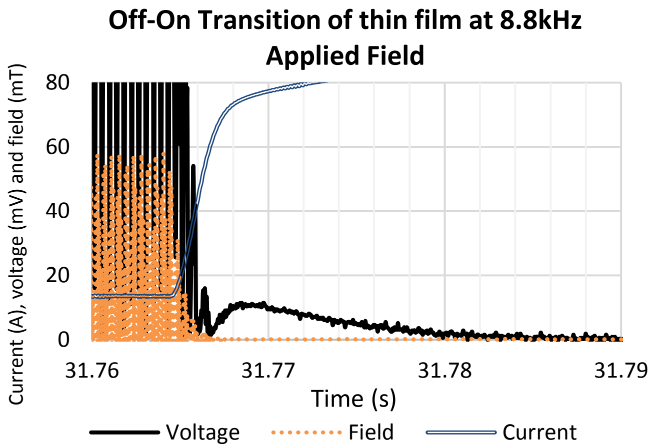

Figure 6: A closeup of the transition from the off-state back to the superconducting state.

VII. Discussion

Results generally agree well with theory and with previous work on thin films and superconducting switches. A result of 9mΩ at 8.8kHz, 50mT is slightly higher than the 5mΩ predicted by equation (1) and may have a small thermal component. However, it clearly shows advantage of using thin films compared to coated conductors which, in published results to date, have about an order of magnitude lower off-state resistance per unit length.

There remains a question as to the performance limit of this switch design. This setup did not allow for full testing of the limits of off-state resistance due to limitations on the electromagnets and the DC power supply. The electromagnets have a large (>4mm) air gap, presenting a high reluctance and are not fully optimized for this application. They also present a very high impedance at higher frequency so higher fields cannot be produced easily. The DC power supply was working in constant-voltage mode. This means when the film is switched while carrying 80A, as seen in Fig. 7, it initially has a high voltage and high current simultaneously, resulting in a high transient power loss. While this power loss reduces very quickly as the current reduces, it puts a high thermal stress on the films. In most real applications, power converters work in an inductive switching or zero current switching mode, so switches are not required to operate in these conditions.

In terms of clear and simple ways to improve this switch design, a higher field strength at high frequency can be pursued. This would be possible with a better electromagnet design, that has a smaller gap, lower inductance and optimized driving circuitry. In addition, cooling can be improved with more liquid nitrogen flow to the film and using a thicker and wider substrate to act as a heat sink. Conduction cooling will also be explored to investigate cryogen-free operation. Power loss can be reduced by using a controllable DC source to vary the transport current synchronously with the switches, as would be the case when the switch is used in a real power converter.

Other immediate future work from this research group includes a fully coupled electromagnetic-thermal simulation using finite element analysis in COMSOL to mirror the exact behavior of AC field switches. In this simulation the temperature distribution, recovery time and maximum electric field across will be analyzed and a comparison between available conductors will be made.

Other ideas building from this work include using these same films but with different methods of actuation into the off-state such as thermal or optical. Also, the possibility of a better candidate superconducting material for switching purposes should be explored. For example, there are other HTS materials in the cuprate family that exhibit higher normal state resistivity which may be of interest. More generally this work may interact with other materials science work that attempts to influence superconductor material properties with external stimuli. For example recent efforts to increase superconducting transition temperature using infrared light [29]. The long-term goal is the development of a superconducting switch with high I_C, high off-state resistance and a fast and efficient means of transitioning between states.

In terms of direct application, these results are promising for using thin films to form HTS switches in high current supplies for superconducting magnets such as flux pumps. Even before any further optimization, these switches provide a good off-state voltage (>100mV) and good I_C (100A) with very little conductor ($3cm^2$) and have fast switching (<15ms). Even scaling linearly from here with no design improvements, a 100mV, 10kA supply could be produced with just $300cm^2$ of YBCO thin film. This would be suitable for many superconducting magnet systems that do not require very fast ramping and presents the possibility of a significant improvement compared to the power density of existing high current superconducting power supplies.

VIII. Conclusion

Results show that a fast acting, compact superconducting switch with a high critical current and high off-state resistance can be realized using YBCO thin films on sapphire, cooled by liquid nitrogen. The immediate next step for the authors is to show that these switches can be used in an HTS flux pumping system with high power density that can be scaled and become useful in real systems.

IX. Acknowledgements

The authors would like to thank Ceraco GmbH for their help providing the thin film samples. James Gawith would like to thank the Woolf Fisher Trust and the Cambridge Trust for funding his PhD.

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