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Power Switches Utilizing Superconducting Material for Accelerator Magnets

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***Abstract*—Power switches that utilize superconducting material find application in superconducting systems. They can be used for the protection of magnets as a replacement for warm DC breakers, as well as for the replacement of cold diodes. This paper presents a comparison of switches made of various superconducting materials having transport currents of up to 600 A and switching times of the order of milliseconds. The switches operate in the temperature range 4.2 - 77 K and utilize stainless steel clad YBCO tape and MgB_2 tape with a nickel, copper, and iron matrix. Results from simulations and tests are reported.**

***Index Terms*—Critical current, HTS, inductive heating, resistive heating**

I. Introduction

POWER switches that utilize superconducting material find application in the superconducting magnet systems of particle accelerators [1]. Such switches could be used instead of warm breakers at the end of long magnet chains resulting in cryogenic savings, for the protection of individually powered magnets, or in fast pulsed magnet systems where the inductive voltages during powering up/down are too high for cold diodes. The switch must have a resistance great enough to allow energy extraction via a dump resistor and a transition time that limits the temperature rise of the magnet. For the Large Hadron Collider 600 A circuits such resistors are 0.2 Ω to 0.7 Ω and the DC breakers open in less than 20 ms [2].

II. Critical Current Measurements

To effectively use high temperature superconductors (HTS) the critical current (I_C) must be known over the full temperature range of operation. For low temperature superconductors such as NbTi the critical surface is well known and can be well described by existing models.

Moreover, the difference between the operating temperature and critical temperature is relatively small, less than 5 K for a NbTi switch operated at 4.2 K in self-field whereas for a Bi-2223 switch operated in liquid helium this could be up to 100 K, depending on the transport current and field. HTS materials such as BSCCO, YBCO, and MgB_2 were more recently discovered and commercialized than LTS materials and their critical surfaces are less well known. In addition to this the manufacturing process also has a strong influence on the properties of the final conductor.

The I_C of various HTS tapes was measured at 4.2 K (Fig. 1) using the CERN critical current test facility [3]. The test facility could supply up to 900 A and a magnetic field of up to 10 T. An HTS sample holder was built to hold samples of length 135 mm with the field parallel to the current direction. A criterion of 1 μV/cm was used with the voltage measured over 10 mm. Tested materials were, copper clad YBCO, MgB_2 tape, and MgB_2 square wire. The YBCO was manufactured by American Superconductor and the MgB_2 by Columbus Superconductors.

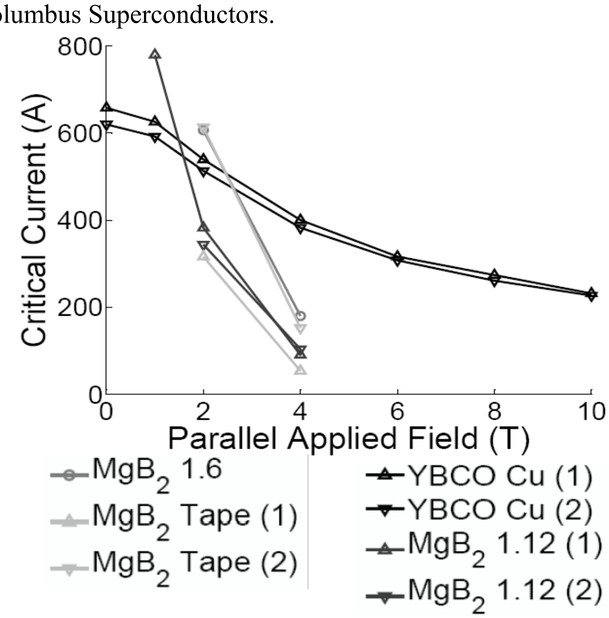

Fig. 1. Critical current test at 4.2 K. Black lines represent copper clad YBCO, downward triangles sample 1, upward sample 2; dark gray lines square section MgB_2 with a side length of 1.12 mm, upward triangles sample 1, downward sample 2; gray line with circles, square section MgB_2 with a side length of 1.6 mm; light gray lines MgB_2 tape of thickness 0.64 mm, upward triangles a width of 3.75 mm, downward a width of 3.95 mm. The narrower MgB_2 tape was delivered a year before the wider one.

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III. Switching via Resistive Heating

One possible way to trigger a superconducting switch is to heat the material above its critical temperature. However, the requirement for this application is that the switch can be made to operate in a few milliseconds. Previously switches having transport currents of 40 A and transition times of a few milliseconds were made and tested in liquid nitrogen [4]. The design of those switches was a multilayer non-inductive spiral containing HTS tape, a resistance heater, and 12 µm thick polyimide insulation. The HTS was joined in the center to form a non-inductive loop, both copper clad YBCO and stainless steel clad YBCO were utilized with the latter having a faster transition time and a higher normal state resistance for a given length. These switches showed that thermally activated switches could achieve switching time comparable to conventional DC breakers; however, the design needed to be scaled up in order to make them suitable for use with accelerator magnets.

To this end a switch based on stainless steel clad YBCO that operated in liquid nitrogen and which had a modular design that allowed scaling of the switch up to the required current levels was designed, manufactured, and tested. The general design of the switch was a standard non-inductive flat coil with a switch back section in the centre to avoid the use of a joint. Similar designs have been successfully used as fault current limiters [5], but in the switch presented here the HTS was co-wound with a resistive heater. Four coils having an average length of 4.8 m (equivalent to 1.65 Ω at room temperature) were made. These coils were connected in parallel to increase the transport current. The heater was a 3.6 Ω (at room temperature) steel tape that was powered by a 1.6 mF capacitor discharge circuit. Electrical insulation was provided by a double layer of 12 µm polyimide insulation; at 1 kV the insulation resistance between the heater and HTS tapes was greater than 25 GΩ. All eight elements were wound concurrently with the purpose-built winding machine shown in Fig. 2. The minimum bending diameter was limited to 50 mm to avoid damaging the tape.

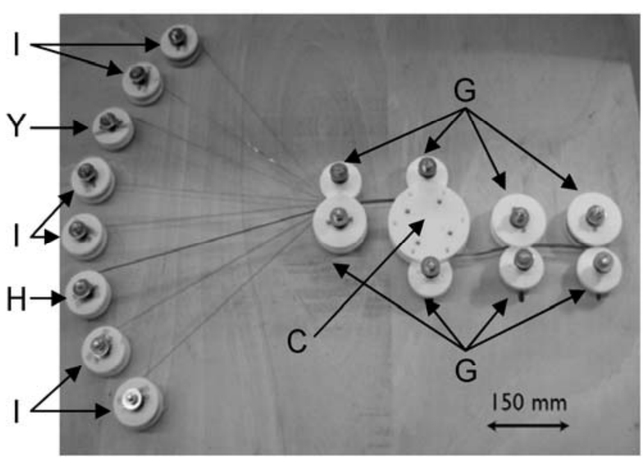

Fig. 2. Winding machine for forming the multilayer switches. I indicates spools of insulation; H, spool of steel tape; Y, spool of YBCO tape; G, guides; C the coil. Friction brakes were mounted on each axle.

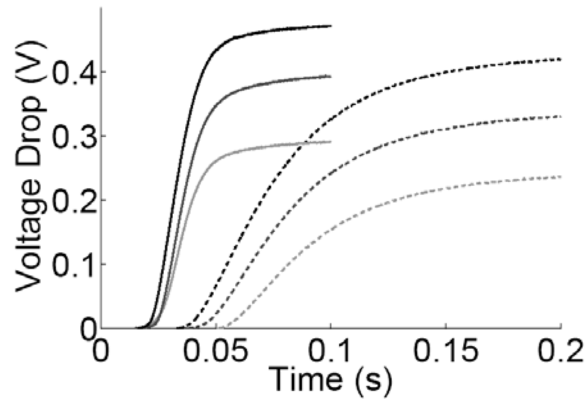

Fig. 3. Voltage traces for one coil (I_C of 55 A) of the switch when individually powered and triggered in liquid nitrogen. Black lines represent a transport current of 50 A, dark gray 40 A, light gray 30 A. Solid lines represent heater energy of 200 J, dotted lines 130 J. The initiation of the heater pulse was at time zero. The traces are an average of a number of tests.

The critical current of each coil was measured with a critical current criterion of 5 µV per coil. The coils were individually powered, with a 16.5 mΩ resistor connected in parallel at room temperature, and triggered over a range of transport currents and heater energies. The voltage drop caused by the resistive leads has been removed from the results presented herein. In total the four coils were triggered over 120 times with no degradation of I_C or switching time being observed. Typical voltages across the resistor for one of the coils are shown in Fig. 3. The switching time was defined as the time taken for the voltage to rise by 0.01 V above the bypass offset. This allowed the comparison between switches transporting different currents or having different final temperatures. Average switching times for the four coils are shown in Fig. 4.

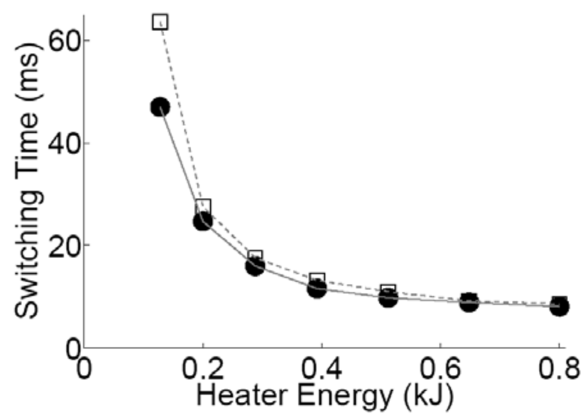

Fig. 4. Measured average switching times for one of the coils (Ic of 55 A) of the switch when individually powered and triggered. Solid circles represent 50 A; Open squares 40 A. Lines are a guide for the eye.

To form a switch having a transport current of 200 A the four coils were connected in parallel, with an 8.4 mΩ room temperature resistor connected in parallel to the switch. The use of the same capacitor necessitated an increase in the maximum discharge voltage from 500 V to 1000 V in order to increase the total heater energy. The switch was tested at various transport currents and heater energies with the switching time being defined as the time taken for the voltage to rise by 0.025 V. Typical voltages across the resistor of the switch operated at 200 A at various heater energies are shown in Fig. 5, average switching times over a range of currents and heater energies are shown in Fig. 6. In total the switch was triggered over 80 times with no degradation of the I_C or switching time being observed.

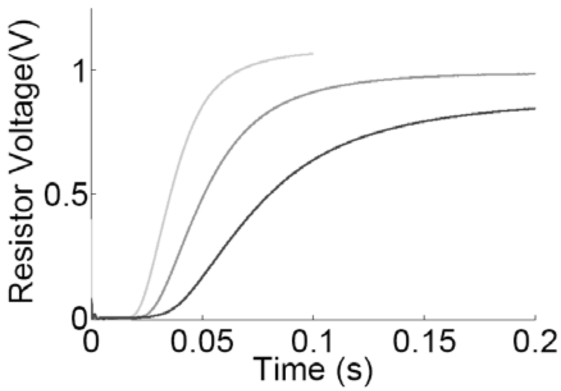

Fig. 5. Voltage traces of the switch carrying 200 A and triggered by 0.8 kJ black line, 0.65 kJ dark gray line, 0.51 kJ light gray line. The traces are an average of a number of tests.

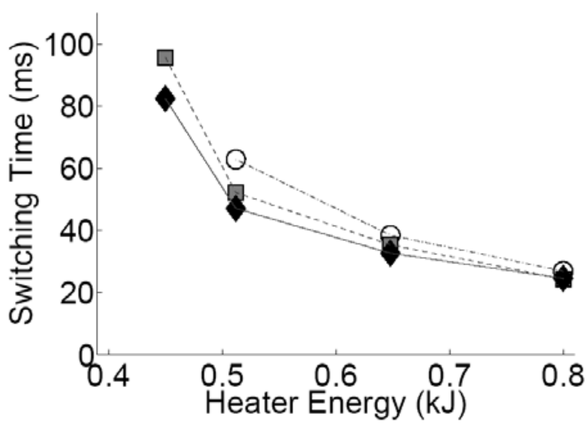

Fig. 6. Measured average switching times for the switch over a range of transport currents and heater energy levels. Black diamonds represent 200 A; gray filled squares 175 A; open circles 150 A. Lines are a guide for the eye.

When the available heater energy was deposited in two of the four coils then these coils quenched faster due to the extra heating with the remaining coils quenched by overcurrent. Fig. 7 shows the voltage across the resistor of the switch triggered in this manner compared to where all four heaters are activated together. In the combined thermal/current triggered switch there is an initially faster response that is dominated by heating of the first two coils, followed by a slower voltage rise corresponding to quenching due to overcurrent of the remaining coils, leading to a switch that is very dependent upon the transport current. Triggering by all of the heaters being fired provided a faster overall switching time that was not as dependent upon the transport current.

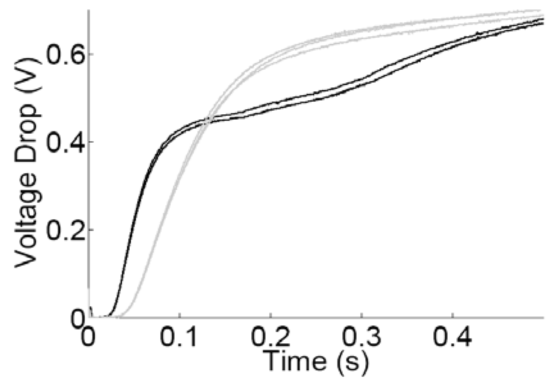

Fig. 7. Voltage traces of the switch operated in liquid nitrogen, carrying 200 A, and triggered with a 0.45 kJ heater. The black lines shows the response when the energy is deposited in only two of the four heaters (two tests), the gray line when it is deposited in all four (three tests).

IV. Switching via Induced Currents

It is possible to cause the heating of a conductor by inducing an alternating current that results in ohmic heating. For a superconductor the induced current must be large as the AC losses as predicted by Norris [6] scale with current. Alternatively the induced current would have to be large enough to exceed the I_C of the material. However, it is possible to cause heating via much smaller induced currents if the superconductor is carrying a direct current onto which the induced alternating current is superimposed.

An inductively triggered switch was made with a design similar to a coaxial solenoidal transformer with an air core. The primary winding was conventional copper wire and the secondary winding was stainless steel clad YBCO tape. 2 mm of polyimide provided good electrical insulation between the windings (measured >100 GΩ at 5 kV at room temperature). Locating the superconductor on the outside of the coil meant that it would be partially exposed to a perpendicular magnetic field increasing the losses [7] and reducing the switching time.

The setup was tested in pool boiling nitrogen with the primary winding carrying a current of 3 A at frequency of 1 kHz. The superconductor was 1.5 m long, carried a constant current of 90 A (I_C of 97 A) and was protected by a 15.4 mΩ resistor connected in parallel at room temperature. The resistance of the current leads meant that there was a bypass current of 2 A through the protection resistor during normal operation. The switching time, the time from the trigger signal that energizes the coil to 0.5 V being developed across the superconductor, was 2.3 s. The coil took 0.3 s to switch on. Six tests were performed with no degradation of the critical current being observed. In the first five tests the transport current power supply was cut off at 0.6 V, in the sixth test a longer run of 20 s was performed, with the voltage trace shown in Fig. 8. Whilst fast switching times were not achieved, these tests showed that such a mechanism could be used to form a switch that utilized HTS material.

The transition time was greater than expected from AC loss formulas due to a low induced current. Thermally triggered transition would occur over longer timescales due to the low coil power (I^2R~7 W), thermal resistance of the insulation, and the thermal mass of the switch. Self heating in the quenched superconductor caused a gradual rise in the voltage drop after the initial switching. When the switch was tested at low currents, transition was not observed further ruling out thermal processes as the main affect and also showing the sensitivity of the loss to the transport current. The switching time could be reduced by increasing the frequency and current in the primary winding and optimizing the coupling of the two windings.

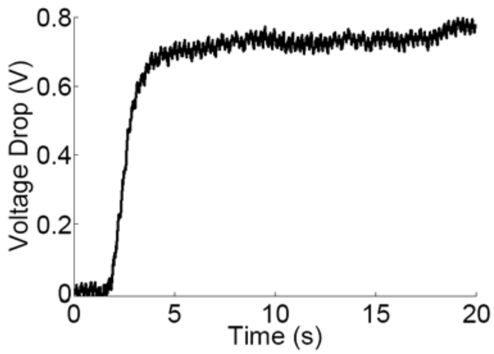

Fig. 8. Voltage trace for switching via an induced current over a 20 s period.

V. Comparison of Modeled Switches at 4.2 K

Most devices that utilize HTS material also operate at high temperatures to benefit from the cryogenic savings that can be achieved. However, for systems such as particle accelerators where there are other components that operate at lower temperatures it becomes possible to operate HTS devices at lower temperatures using the same cryogenic system. Switches operating in such conditions were modeled. The tapes were YBCO with stainless steel cladding (I_C of 650 A at 4.2 K), and MgB_2 in a Ni/Cu/Fe matrix (I_C of 1 kA at 4.2 K). The model was a 1 m long straight switch that had a resistive heater along its length with polyimide insulation between the electrical elements. The YBCO tape carried 600 A, the MgB_2 600 A and 960 A. The heater was powered with a 2 kJ capacitor discharge pulse. The model had a zero applied magnetic field, adiabatic boundary conditions, a non decaying transport current, and an infinite n-value. The modeled resistances are shown in Fig. 9. Resistivity values that had been previously measured in Southampton were used [4].

The switches carrying 0.96 I_C had a similar initial transition time due to the same heater energy and insulation being used, as well as their similar T_C at these transport currents; 9 K for the YBCO, 9.6 K for the MgB_2. When carrying 600 A the MgB_2 switch had a T_C of 27 K. The resistance of the YBCO based switch rose faster due to its higher normal state resistance. The modeled MgB_2 tapes contained Cu stabilization; with more resistive matrices MgB_2 tapes could have greater applicability to switch usage. It is also noted that if the YBCO based switch was operated at 77 K and carried 0.96 I_C (at 77 K) it had a similar transition time to the one operated at 4.2 K, but a slower rate of increase in resistance, and thus resistance, after 1 ms due to the greater power dissipated in the tape carrying 600 A.

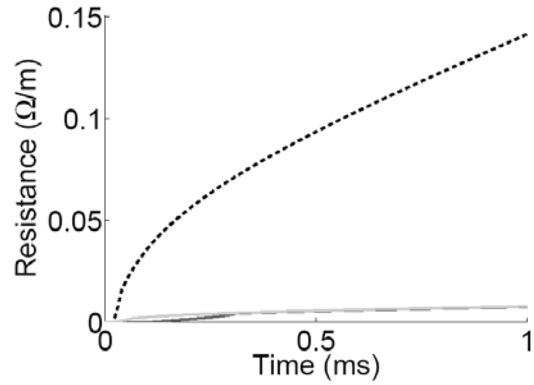

Fig. 9. Modeled resistance for switches operating at 4.2 K and formed of stainless steel clad YBCO carrying 600 A (dashed black line), and MgB_2 with a Ni/Cu/Fe matrix carrying 600 A (solid dark gray line), 960 A (solid light gray line).

VI. Conclusion

It has been shown that it is possible to form power switches that utilize HTS material for use with accelerator magnets. Two triggering mechanisms have been proposed, the first, resistive heating, has been scaled to high currents and millisecond switching times. The second, inductive heating, is still preliminary but shows that a contactless triggering mechanism can be used. The transport currents and switching times of such switches can be improved by operation at lower temperatures that are often available in particle accelerators.

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References

[1] A. Ballarino, K. H. Meß, and T. Taylor, "Extending the Application of HTS in Particle Accelerators", *Journal of Physics: Conference Series*, vol. 97, 012288 (6pp), 2008.

[2] K. Dahlerup-Petersen, F. Rodriguez-Mateos, R. Schmidt, and F. Sonneman, "Energy Extraction for the LHC Superconducting Circuits", LHC Project Report 484, CERN, 2001.

[3] T. Boutboul, C. H. Denarie, Z. Charifoulline, L. Oberli, and D. Richter, "Critical Current Test Facilities for LHC Superconducting NbTi Cable Strands", LHC Project Report 520, CERN, 2001.

[4] S. A. March, A. Ballarino, C. Beduz, K. H. Meß, and Y. Yang, "Towards the Design of Power Switches Utilizing HTS Material". *Journal of Physics: Conference Series*, vol. 97, 012002 (6pp), 2008.

[5] W. Schmidt, H. P. Kraemer, H. W. Neumueller, U. Schoop, D. Verebelyi, A. P. Malozemoff, "Investigation of YBCO Coated Conductors for Fault Current Limiter Applications," *IEEE Transactions on Applied Superconductivity*, vol.17, no.2, pp.3471-3474, June 2007.

[6] W. T. Norris, "Calculation of Hysteresis Losses in Hard Superconductors Carrying AC: Isolated Conductors and Edges of Thin Sheets", *Journal of Physics D: Applied Physics*, vol. 3, p489, 1970.

[7] P. Suarez, A. Alvarez, B. Perez, D. Caceres, E. Cordero, J. M. Ceballos, "Influence of the Shape in the Losses of Solenoidal Air-Core

Transformers," *IEEE Transactions on Applied Superconductivity*, vol.15, no.2, pp. 1855-1858, 2005.