Electrical and Thermal Behavior of Patterned Superconducting Disks *

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Abstract — **An apparatus for the investigation of low and high-T_c superconducting spirals has been designed and built. The device is capable of measuring the chcaracteristic of superconducting spirals. The superconductor spirals are on a normally conducting substrate. The normally conducting substrate serves as a shunt between the superconducting turns, serving as a distributed quench protection resistor. Samples with both high and low electrical resistance substrates have been tested on this apparatus. Preliminary results of the tests of both high-T_c ($Bi-Sr-Ca-Cu-O$) and low-T_c ($Nb-Ti$) thick-film spirals have been investigated. Current distribution in films during quench has been studied experimentally. Generation of normal zone and hysteresis current-voltage characteristics have been discovered in high-T_c superconducting spirals on silver plate. It is shown that frequency of generation of normal zone depends at under certain conditions (transient current, magnetic field, temperature and resistivity of substrate). The results are being analyzed with models.**

I. INTRODUCTION

The large upper magnetic field of high-T_c superconductors gives a possibility in principle to build efficient magnets, operating at elevated temperatures (higher than $4K$). A proposed method for building magnets is to manufacture the ceramic superconductor in spirals on substrates, with electrical contact on their ends [1].

This construction, referred to as Superconducting Bitter magnets, offers some advantages to the construction of high temperature superconducting magnets. Quench protection is an issue with high-T_c magnets. High-T_c magnets, especially when operated at elevated temperatures, are characterized with a low velocity of quench propagation. In superconducting Bitter magnets, the resistive shunts (actually the substrate) allows the current to bypass a normal zone in the superconductor, after which the heated zone cools down. At the end of the cool down, the current transfers back to the superconducting element, with minimal dissipation of energy.

In this context, the electrical behavior of superconducting thick-film spirals shunted with resistive elements is of considerable interest. In order to provide this understanding, the distribution of current, temperature and voltages needs to be investigated.

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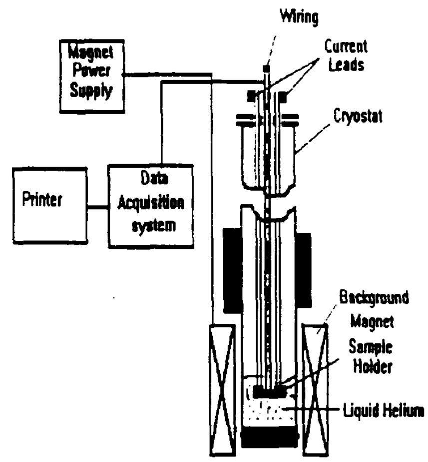

Figure 1: Block diagram of experimental setup

In this paper, preliminary analysis of superconducting spirals patterned on silver substrate of different thickness are presented. This paper describes experiments to investigation of current-voltage distribution in samples of high-T_c on Bi-based spirals with different resistivity of the substrate material.

II. APPARATUS

The measurements are made in magnetic fields up to $10T$ and temperature $4.2K$. The experiments have been carried at the Francis Bitter National Magnet Laboratory.

Experimental apparatus used for test of high-Tc spirals and block diagram of the computer controlled data acquisition and analysis system are shown in Fig. 1.

$I-V$ characteristics are measured by using four-probe method. Several voltage probes have been connected to the superconductor. The data was acquired with a 8-channel recorder. The data acquisition system has been upgraded to 16 channels, with direct computer interface. The system is capable of directly recording voltages as low a 10μV. With a pre-amp, much lower voltages should be feasible. The new data acquisition system will be used to simultaneously collect signals from as many as 14 voltage taps.

The experimental procedure consisted in setting both magnetic field and conductor current, allowing transients

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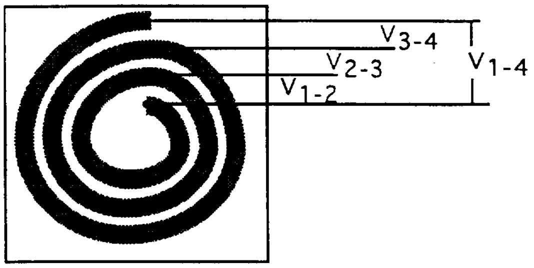

Figure 2: Schematic of voltage tap connections of single sided sample made of Nb-Ti on stainless steel

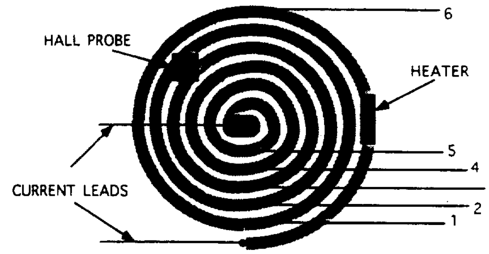

Figure 3: Schematic of disk, showing location of voltage taps, current leads, Hall probe and heater, for single sided sample made of BISCO 2212 applied on silver substrate.

to die down, and then activating a heater attached to the substrate. The heater causes the superconductor near the heater to become normal.

The magnetic fields generated by the disks were detected by a Hall probe set on the silver plate.

III. SAMPLES

Both samples with high and low-T_c have been used. The low-T_c tape was manufactured at the Plasma Fusion Cernter, while the high-T_c tape was manufactured at Los Alamos National Laboratory.

A. Nb-Ti TAPES

A $Cu - Nb/Ti - Cu$ composite was used for these experiments. The characteristics of the tape have been described in reference [2]. The tape was soldered to a stainless steel substrate, using $Pb - Sn$ solder. The tape was patterned mechanically. A shcematic of the $Nb - Ti$ sample is shown in Fig. 2.

The purpose of the test was to both test the setup and to study the behaviour of the shunted superconductor with a well understood tape.

B. BISCO TAPES

Nominal $Bi_2Sr_2CaCu_2O_y$ powder was processed by splat-quenching in order to obtain a homogenous, dense material. Details of this process are explained in detail elsewhere [3]. ICP analysis of the resulting powder used in the present work revealed a Ca-poor composition of $Bi_{2.09}Sr_{2.03}Ca_{0.78}Cu_{2.11}O_y$. A slurry of this powder in isopropanol was used to fill the groves of a patterned silver disk. During isothermal melt processing, precursor films are heated in an Ar atmosphere at 10C/min to a temperature between 760C and 860C and held for one hour. After this step, the gas flow is switched to 10% O_2 (balance Ar) to oxidize the sample and form the Bi-2212 phase. After an additional 15 hours, the samples are cooled at 5C/min to room temperature. Bi loss during the melting process in Ar appears to have been significant only for samples processed above $820C$. During processing of the latter films, the portion of the quartz tube outside the furnace was coated with a dark yellow film. The average thickness of each film was determined by taking several micrographs from random areas of two or more cross-sections and measuring the thickness from three spots on each micrograph. Typical thicknesses ranged from $10\mu m$ to $20\mu m$.

The tapes used in the experiment were produced by mechanically patterning a $2.5 \times 2.5cm^2$ silver sheet with a spiral. The groves in the silver were about $100\mu m$ deep. The groves formed were filled in with powder, and the sample was processed as described above. A schematic diagram of the one of the spiral samples is shown in Fig. 3.

Silver tapes have dimensions $25 \times 25mm^2$. Details of fabrication procedure of samples have been reported elsewhere. [3]. The parameters of samples are listed in Table 1.

	#1	#2
Spiral length (mm)	24	30
Number of turns	4	5
Cross section of HTSC (mm^2)	0.09	0.09
Inner diameter of spiral (mm)	6	6
Outer diameter of spiral (mm)	25	25
Cross section of Ag plate (mm^2)	25	12.5

Table 1: Parameters assumed for the modeling of Ag-disks

IV. EXPERIMENTAL RESULTS

A. Nb-Ti SPIRAL

Voltage-current characteristic for different turns of $Nb-Ti/Cu$ spiral during quench are shown in Fig. 4. The non-uniform critical current density in this spiral causes a gradual transition from superconducting to the normal conducting state.

The figures shows that the innermost turn quenches at $\sim 75A$, the second quenches at $\sim 100A$ and the third turn quenches at $\sim 140A$. At that current, the entire spiral is normal. $V_{1-4} = V_{1-2} + V_{2-3} + V_{3-4}$. The resistance across the voltage taps V_{1-2} and V_{2-3} is about 1.3×10^{-5} Ω. The total resistance for a fully quenched spiral is $\sim 10^{-4}\ \Omega$.

B. H-Tc SPIRAL

Typical oscillograms of voltage on different turns of HTSC spirals are shown in Fig. 5 through 7.

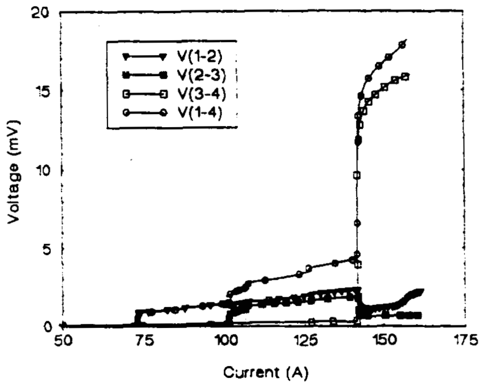

Figure 4: $V - I$ characteristics of $Nb - Ti$ spiral

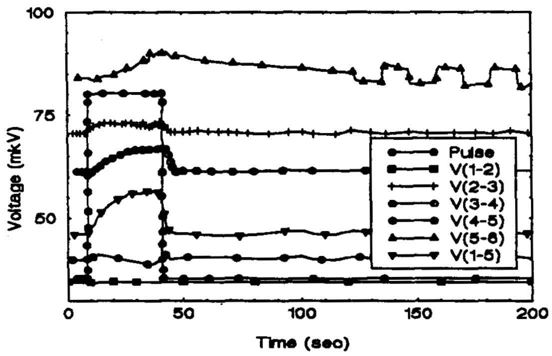

Figure 5: $V - I$ characteristics of high-T_c, #1 spiral. $B = 0$ T, $I = 70$ A

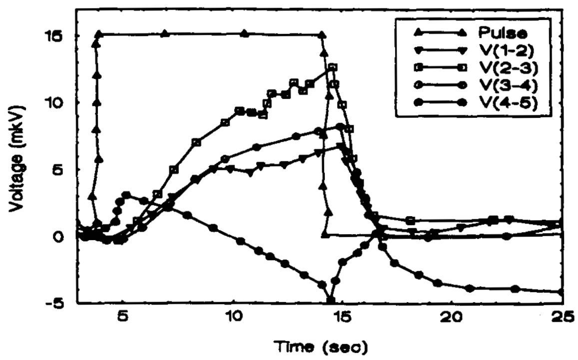

Figure 6: $V - I$ characteristics of BISCO spiral. $B = 0T$, $I = 96A$

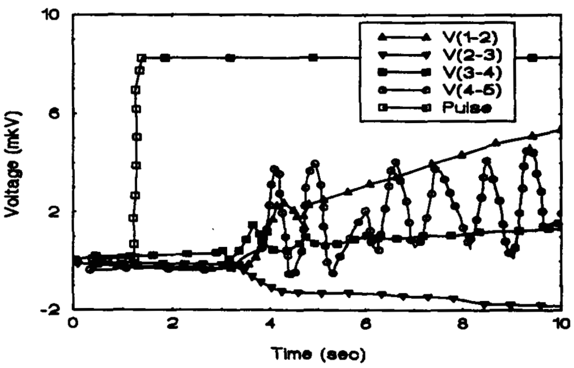

Figure 7: $V - I$ characteristics of BISCO spiral. $B = 0$T

The initial quench of the spirals was caused by the application of a current pulse (20 V, $\sim$ 1 A) into a heater placed on outer turn of spiral, as shown in Fig. 3.

Fig. 5 shows the voltages across the nodes indicated in Figure 3. for the #1 spiral. These measurements were made at 0 T, 4.2 K and different levels of constant transport current in samples. After the pulse is terminated, the voltage decreases with a time constant of $\sim$ 100s. 100s after the termination of the heating pulse, non-linear oscillation in the tape are observed. The oscillations start as a small sinusoidal signal in the middle turns of the tape, and suddenly becomes large and square-wave shape in the innermost region.

The character of quench of spiral changes with the level of applied current. The frequency of generation depends on the transport current, and has only been observed in the high-T_c spiral.

Results for different sample are shown in Fig. 6. The voltages of the different turns increase monotonically during the application of the pulse, with a time constant on the order of 5 s. At the termination of the heat pulse, the voltages drop with a time constant on the order of 1 s. Note the reveral of the direction of current flow between the nodes 4 and 5, occuring shortly after the application of the heating pulse. The reversal is not due to inductive effect, since the inductive voltages are much smaller than this.

At even higher current, the behaviour is different. All the turns in the spiral quench, with the innermost turn with $B = 0T$ and $I = 180A$, shown in Fig. 7 A. However, the current in a region in the middle of the coil reverses direction, as in the case of Fig. 6 (V_{2-3} is of opposite polarity to the voltage across the other voltage taps). In addition, the voltage in the innermost turns show a large oscillation (although sinusoidal in this case), with a perioud of about $1s$. The frequency of oscillation in this case is much higher than that in Fig. 5.

The quenching process in high-T_c superconducting spiral on silver plate is not simple. Because of the large size of the stabilizer, if normal zone appears, the current in this region redistributes into stabilizer. Joule power decreases and superconductivity is recovered.

Voltage-current characteristic of HTSC spiral at magnetic field $5T$ is presented in Fig. 8. The voltage across the current leads, V_{1-5} is shown as a function of the current. The voltage across the spiral experiences hysteresis. Increasing current results in lower voltages than when the current is decreased. There are also voltage humps as a function of current. Note that the voltage humps during ramp-up do not correspond with the humps during ramp-down. The above phenomenon is probably connected with the resistive domains (normal zone regions of finite size [4].

Preliminary experiments with a Hall probe have been performed. The results are shown in Figure 9. This

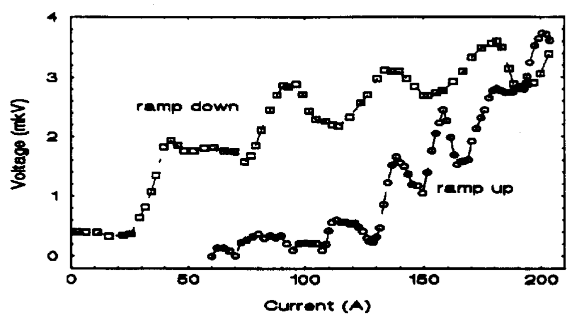

Figure 8: $V - I$ characteristics of BISCO spiral. $B = 5T$

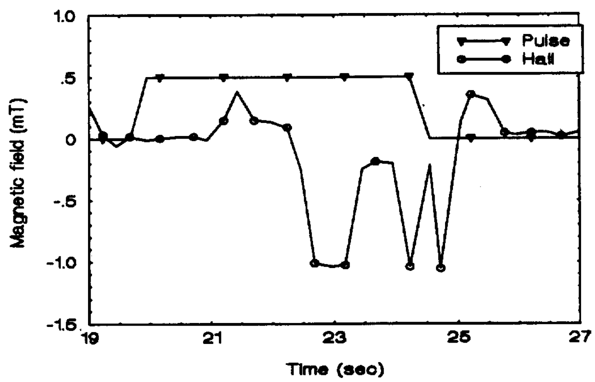

Figure 9: Signal from Hall Probe at edge of BISCO spiral. $B = 0T$, $I = 180A$

picture shows the time changes of magnetic field (with no applied background field, $I = 180A$). Magnetic field is measured by Hall probe is placed on face of Ag-plate (Fig. 3). The oscillations in the magnetic field start 2 s after the heating pulse is applied. Again, the period of oscillation is on the order of $1s$.

V. DISCUSSION

The calculated resistance across the turns for the $Cu-Nb/Ti$ composite sample varies between 1.3 and 5×10^{-5} Ω. The results indicate indeed that the turns are quenching sequentially, starting first with the innermost turns. The widths of the turns are not constant. Therefore, it is not surprising that the critical current for the different turns is not constant.

The dynamics of normal zone propagation can be investigated by using the heat and voltage balance equations for thermal and electrical processes occurring in the real spiral [4]. It is impossible to find an exact analytical solution for current distribution in this system, because there is dependence of thermo- and electrophysical parameters of the current-carrying element and critical current of high-T_c superconductor on temperature and magnetic field. The problem of normal zone propagation in large composite superconductors have been studied many authors both analytically and experimentally [5-4]. Different types of behaviour in thermal quenching and superconductivity recovery have been identified by S.Y.Seol and M.C.Chyu [5], where the thermal and inductance coupling effects of sample have been ignored.

A model for normal zone propagation was proposed by Kovner [4]. In this model the composite is considered as an equivalent electrical circuit, consisting of two connected circuits, representing superconductor and stabilizer. The numerical simulation of equations describing the dynamics of normal zone showed the existence of propagating domains in the superconducting composite. The physical mechanism of normal zone propagation in high-T_c spiral on silver plate can be qualitatively explained. If a part of superconductor undergoes a normal transition, the current starts to redistribute between the superconductor and stabilizer. After the redistribution of current is complete, the conductor cools down. When the temperature crosses the critical temperature, the superconducting state is recovered, and current rediffuses back to superconductor. This process can provide an explanation to the characteristic oscillations shown in Fig. 5 to Fig. 9.

VI. CONCLUSIONS

In this paper, preliminary result of normal zone propagation in shunted superconducting spirals have been presented. It is shown that if a part of superconductor becomes normal, the current starts to redistribute between the superconductor and substrate. After the removal of the heating source, the spiral cools down and when the temperature crosses the critical temperature, the superconducting state is recovered, and the current reverses to its original flow pattern. Large heating inputs are required to quench the high-T_c spirals. The propagation of the normal zone and, in particular, redistribution of the current, is being further investigated. Theoretical calculation of electrical and thermal behavior of patterned superconducting disks are presented in an accompanying paper.

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