DYNAMIC BEHAVIOR OF HTSC OPENING SWITCH MODELS CONTROLLED BY SHORT OVER-CRITICAL CURRENT PULSES

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INTRODUCTION

A number of proposals exist for using superconductors as opening switches for pulsed power generators with inductive energy storage [1-3]. As far as is known, they have not actually been used in full-scale pulsed power systems for many reasons. One of them is connected with limitations in the material properties of superconductors available, in particular, high conductivity in their normal state, necessity to use liquid helium systems, etc. Recently, however, some changes have occured in the situation. Developments in superconducting materials have led to new "high-temperature" oxide ("ceramic") superconductors which have critical temperatures greater than 90 K, well above the temperature of liquid nitrogen (77 K). HTSC can carry high currents (~1-10 MA/cm^2) in their superconducting state and have moderately high resistivity in their normal state (~mΩ·cm). These properties open the possibility of making a superconducting fast opening switch, but many problems still remain and must be solved before using the new materials in new applications. There is, therefore, a need to continue experimental researches to understand new features of materials, what properties are relevant and what are the actual limitations.

One of the important questions is the dynamic behavior of the switches during the opening. It depends on the method used to quench a superconductor to the normal state. In this paper we present results of experimental research of dynamical properties of thin films of $YBa_2Cu_3O_7$ HTSC-switch models under action of short overcritical current pulses to test this method of control of fast (of nanosecond range) high-power opening switches for accelerator applications.

EXPERIMENTAL SETUP

The experimental setup consists of a cryogenic system (dewar) with inserted into liquid nitrogen stainless cylinder-helium gas filled container of a test sample assembly, nanosecond pulse generator and a set of current and voltage monitors connected to a Tektronix storage scope. Several cable-type generators were used in the experiments to generate the fast rising (less than 2 ns) current pulses of 15 to 500 ns duration. By controlling of the charging voltage, the amplitude of the pulses is varied over a wide range, typically up to 10 I_{CR}, where I_{CR} is the critical current for the HTSC sample under test.

All HTSC samples used in the experiments are epitaxial thin films prepared by laser sputtering of the "standard" HTSC composition $YBa_2Cu_3O_7$ on the substrate of $SrTiO_3$. The preparation method and the results of the detailed research of the film properties are described in [4]. The critical temperature for the samples used in the experiments is in the range 89.5-90 K, the critical current density at T=77 K is about 10^6 A/cm^2, and film thickness – 200-300 nm.

The simplified sketch of the HTSC opening switch model is shown in Fig.1.

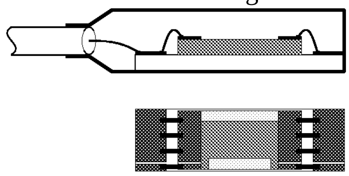

Fig.1. Flat coax model of HTSC switch

The substrate with the HTSC film is installed between two metal strips forming together with the sample and current monitor (not shown in Fig.1) a low-inductance flat coaxial, connected to the current pulse coaxial feeder. The dimensions of the substrate with the film deposited are 10x10 mm^2 and 1 mm thickness. To form the samples with a predicted value of the critical current I_{CR} and to remove the end effects the working area is shaped by a laser cutter as a narrow "bridge" between two wide contact zones. The length of the "bridge" is about 4-5 mm and the width is in the range 0,6 – 4mm to keep the I_{CR} close to 2 A for different samples. For correct measurements of the "bridge" voltage drop, the contact zones are split into two areas – current part (wide) and potential. Thin additional cables (not shown in Fig.1) are connected to the potential ends of the sample and resistors of the current monitor.

EXPERIMENTAL RESULTS

Dynamic impedance response of the switch models on the overcritical current pulses was measured using the single nanosecond pulses as well as trains of several pulses to distinguish the electrodynamics and thermal effects.

The typical dependence of the switch voltage versus the switch current (V-A curve) measured for sample #3 at the flat top of the pulses is shown in Fig.2.

The second curve in Fig.2 is the resistance dependence R vs I calculated for data measured. For current levels below I_{CR}=1.9A the voltage and the resistance are close to zero level and the sample is in the SC-state. For currents higher than I_{CR} , the voltage and the resistance are far enough from zero level and the sample is switched to a resistive state. This state is nonlinear. The voltage is not proportional to the current and the resistance increases with the current level. Most important for the opening switch application feature of this state is the relatively low level of resistance. At currents as high as 5 I_{CR}, it is almost one order of magnitude less than the normal state resistance measured near T_{CR}.

For comparison the “cooling” curve is given in Fig.3 – resistance vs time during the cooling cycle for the same sample # 3, which has the highest normal state resistance for all sample tested. The curve shows the level of the sample resistance at room temperature (about 45 Ohms) as well as at T_{CR} - just before a fast jump to zero level, as indicated (about 14 Ohms). Note that there is no difference in the resistance measurements done by different methods at strongly different currents. This means the normal state resistance is independent of the current level.

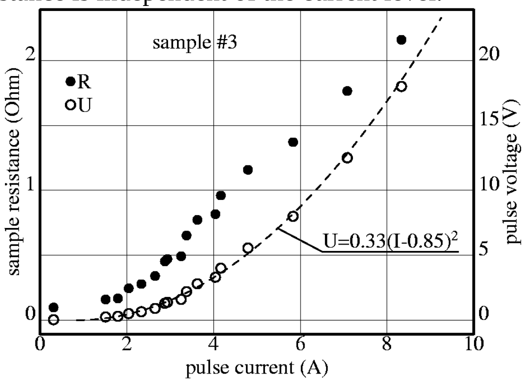

Fig.2. Voltage vs. current for 400 ns pulses

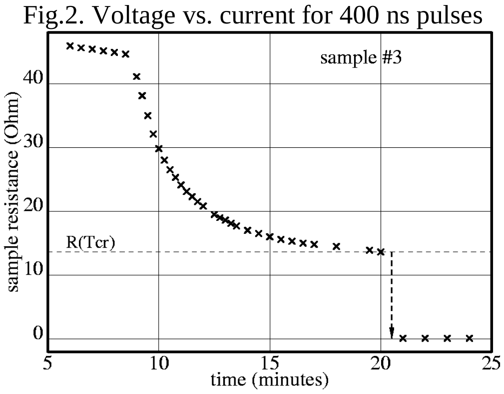

Fig.3. Resistance vs time during cooling cycle

The dynamics of the opening of the switch models is illustrated by Fig.4, showing the scope traces of the voltage recorded for several currents during the test of the sample #1 ($I_{CR} \approx 2A$, $R \approx 8$ Ohm at room temperature). The traces shown in Fig.4 correspond to the current pulses with amplitudes 5, 6, 11 and 12 A.

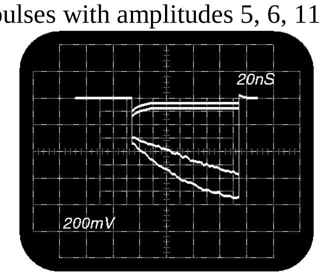

Fig.4. Oscilloscope traces for sample #1

For currents lower than 3-4 I_{CR}, the voltage trace has a quasi-rectangular shape. It is close to that of the current pulse except for the inductive spike at the front, well visible for small overcritical currents when the resistive component of the voltage V=IR is small compared with the inductive one V=Ldi/dt. This means that the resistance is constant during the pulse for a given current level. Detailed analysis of the initial parts of the voltage and current pulses showed no time delay between them at I> I_{CR} within the scope resolution time of 3 ns – the switching to a resistive state when the I_{CR} is reached is faster than this resolution. The voltage is not constant during the pulse for currents higher than 8A for the sample given. Increasing of the voltage at the end of the current pulse indicates increasing of resistance. It may be a thermal effect of the sample, temperature rising due to power dissipated during the pulse.

To clarify the effect observed, a train of nanosecond current pulses was used for sample testing. It was generated by the mismatched cable generator in a mode when $Z_{Load} << Z_G$. The amplitude of the second pulse in the train was $I_2 \approx 0{,}8\ I_1$, where I_1 is the amplitude of the first pulse, of the third - $I_3 \approx 0{,}65\ I_1$. The time interval between the pulses in the train was 30 ns. The dependences of the resistance of sample #1 measured at the beginning (t=15 ns) and the end (t=95 ns) of the first and second pulses (t=100 ns) of the train versus the current of the first pulse are shown in Fig.5. The corresponding curves are marked as 1b, 1e, 2b and 2e. As was mentioned, starting from some current the curves are split for two branches, indicating that the sample resistance is not constant during the pulse. It is possible to see that the splitting takes place for the second pulse first. By the beginning of the second pulse in the train, the resistance of the sample is about the same as at the end of the first pulse. It looks like a “memory” effect when the sample keeps for some time the same resistance as measured at the end of the pulse.
The same effects were observed for all samples tested, but the voltage rising during the pulse took place at different current levels for different samples, typically at a higher level for most of the samples.

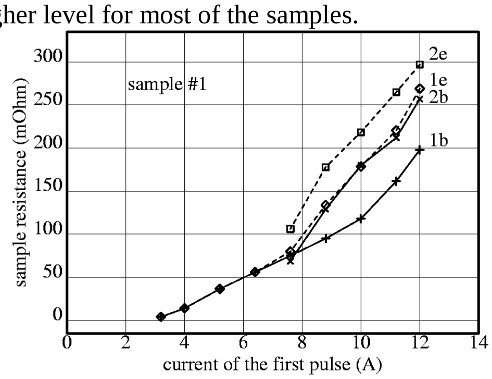

Fig.5. Resistance value at start (b) and at end (e) of pulse for the first and second pulses in train

CONCLUSIONS

Dynamical properties of thin epitaxial film of $YBa_2Cu_3O_7$ HTSC-opening switch models under action of short overcritical current pulses were measured to test this method of control of fast (of nanosecond range) high-power opening switches for accelerator applications. It was found that overcritical current pulses switch HTSC to a resistive state during a short time small compared with the rise time of the current pulse. For this state the resistance of samples is a nonlinear function of the current and is much smaller than that for the normal state. The effects observed indicate a complicated picture of processes taking place under action of short overcritical currents.

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