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Quench characteristics of Ag/AuBi2223 HTS-stainless steel stack used for the hybrid current leads of the Large Hadron Collider

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Abstract. The quench characteristics of Ag/Au sheathed Bi2223 tapes have been investigated in an adiabatic condition and in a configuration similar to that used in hybrid high temperature superconducting current leads, namely the 13000A leads used for the Large Hadron Collider at CERN. A specialised rig was designed and constructed to provide a carefully controlled environment. The samples were prepared from HTS tape soldered onto a stainless steel substrate with a number of temperature sensors at various positions along the length of tape. One end of the lead (cold end) was maintained at 6K using G-M cryo-cooler whereas the temperature of the other end (warm end) can be varied and maintained at temperatures up to 100K. The thermal runaway currents (quench currents) at various warm end temperatures (in the range of 40-100K) were determined. The temperature evolutions at various locations along the tape were recorded at different top end temperatures and currents. The effect of the stainless steel mechanical reinforcement on the thermal properties of the stack was also investigated and presented.

1. Introduction

The comprehensive implementation of high-temperature superconducting (HTS) current leads in the Large Hadron Collider (LHC) at CERN [1] represents a major breakthrough for large scale practical applications of high temperature superconducting materials. After more than ten years of intensive R&D by CERN with several external partners, the production design was completed for three classes of current leads rated at 13000A, 6000A and 600A with different performance specifications by the end of 2003. A total of about 3 MA of current is to be transported by these current leads using 31 km of HTS conductors.

The basic concept for a HTS current lead is given elsewhere [1-4]. The hybrid lead is divided into two sections. The upper section is made of copper, as in a conventional current lead whereas the lower section consists of HTS soldered onto a stainless steel tube. The lower end of the HTS element is cooled by liquid helium, whereas the top part is cooled to about 50K by 20K helium gas. By using HTS materials in these hybrid HTS current leads, CERN can make a substantial reduction in the cryogenic load of the LHC machine [4].

One of the most important issues with these leads is the quench characteristic of the HTS part, which for example can be caused by a failure of the 20K helium gas cooling. Due to quenching, the temperature of the composite HTS part of the current lead will increase continuously unless the quench is detected in time and the current is switched off. Continuous monitoring of the temperature and voltage can detect the early stages of quench and trigger an immediate action to prevent further expansion. In case of resistive transition of the high temperature superconductor, the lead should be able to discharge the magnet current at its nominal decay rate, corresponding to a time constant of about 120 s, without overheating above 200 K [1].

In this study, the quench characteristics of Bi2223 superconducting tapes have been investigated in an adiabatic condition without self generated vapour cooling, as in the 1300A hybrid high temperature superconducting current leads used for the at LHC at CERN. In our experiment, the current leads were quenched either by increasing the transport current above the critical current at the top end, or by increasing the top end temperature above the current sharing temperature.

2. Experimental

The experimental test rig consists of a stainless steel outer vacuum vessel, which contains a two stage G-M cryo-cooler and a sample holder. The test sample was produced as a HTS lead with a stainless steel substrate and in a similar way to the HTS sections as used in 13000A current leads produced at CERN. A length of Bi-2223 tape (260 mm long) was soldered to a stainless steel substrate of thickness 0.8 mm and width 3.8 mm. The substrate was cooled with a 0.2 mm thick layer of tin in order to ensure a homogenous mechanical bond with low thermal and electrical resistance. Two types of superconducting tapes with AgAu alloy sheath were investigated, 37 filament NST and 55 filament AMSC Bi2223 tapes, with critical currents of 40A and 110A at 77K and self field, and a volumetric superconductor filling factor were 0.3 and 0.35 respectively. The dimensions of these tapes were 3.2 mm wide and 0.2 mm thick for NST tape and 4.2 mm wide and 0.2 mm thick for the AMSC tape. The percentage of Au in the sheath of the NST tape was 4% and was 5% in the AMSC tape. In order to eliminate the possibility that the return HTS lead may quench and affect the experimental conditions, it was “reinforced” by using four tapes (two HTS tapes soldered on each side of a stainless steel strip).

The HTS current leads were soldered to two copper termination blocks as shown in Figure 1. The bottom block (cold end) was thermally anchored to the second stage of the cryo-cooler and maintained at 6K, whereas the top block or ‘hot end’ consists of two electrically insulated copper terminals. Each HTS lead was soldered inside 15 mm deep grooves in the copper blocks. Due to the slenderness of the assembly, fibreglass rods were used to provide further mechanical strength.

The current is fed through a pair of copper current leads, which were thermally attached to the first stage of the cryo-cooler using Kapton insulated copper clamps. The current leads enter the inner space of the vacuum vessel through the bottom stainless steel flange via ceramic insulating seals.

The test sample was instrumented with ten thermocouples, which were soldered at various locations along the lead. The top block or ‘hot end’ of the sample holder was conduction cooled to the 1st stage of the cryo-cooler via the current leads and the temperature can be varied in the range of 65 K to 100K using PID control and a silicone Diode in the copper block. The sample and the second stage of the cold head were thermally shielded using copper sheet, which is connected to the first stage cold head and layers of superinsulation. Thermal equilibrium of the test sample was established by controlling the end temperatures prior to current injection. Several (up to 4) test runs were carried out to identify the value of “quench” current *Iq*. This is the lowest current which will cause a noticeable propagating increase in the voltage and temperature.

3. Results and Discussions

3.1. Quench Current and Temperature Profiles

Figure 2 presents the quench current of the HTS leads as a function of the top end temperature T_{top}. It can be seen that the quench current (Iq) decreases with increasing top end temperature. At high temperatures, and Iq is higher than the corresponding critical current (I_c) of the tape, At low temperatures it approaches the critical current of the tape.

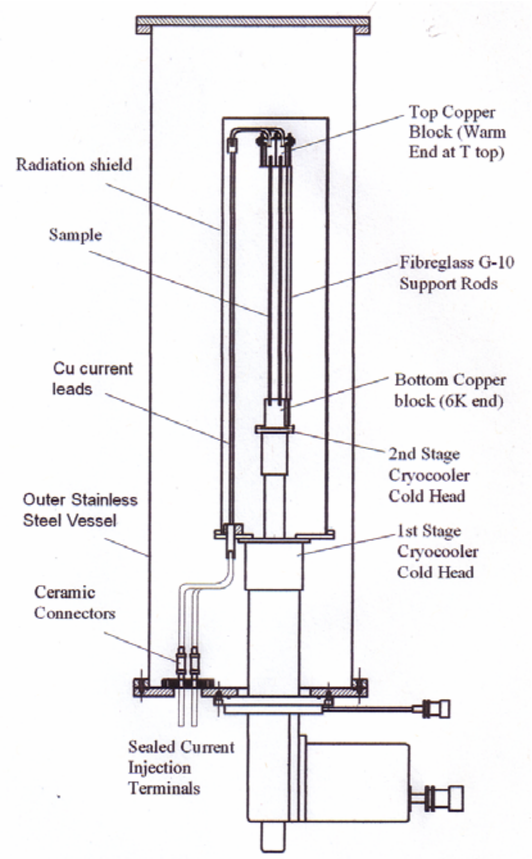

Figure 1. A Schematic representation of the test rig,

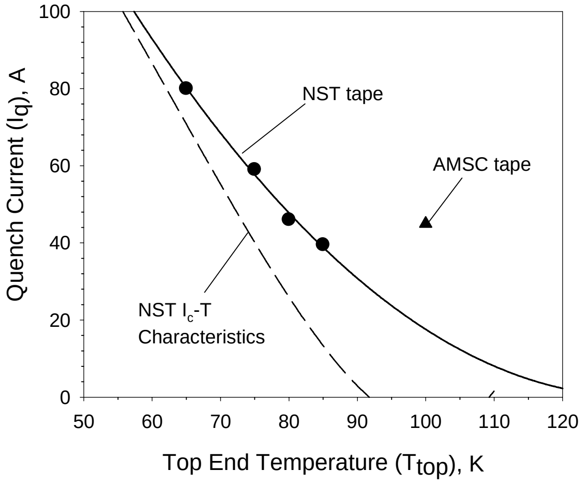

Figure 2. Quench current as a function of top end temperature of NST tape.

Once the quench current was determined, the temperature profiles along the lead were measured at various times following a quench caused by a transport current at the corresponding quench current, as shown in Figure 3. In all the graphs, the initial temperature profile at t = 0 corresponds to a condition when there is a 3mV voltage developing across the entire conductor. This criterion was chosen similar to that used by CERN to detect the quench and the start of current discharging. As the quench is initiated, a ‘hot’ zone forms which grows with time and propagates further into the conductor, resulting in disturbance of the steady state profile. However, it seems that the normal zone is localised at the top section of the lead (0-100mm) and does not extend to cover the entire length of the HTS lead. Temperatures above 240K were not recorded as they are beyond the range of our data acquisition system. From Figure 3, the extent of the normal zone penetration into the lead increases with decreasing quench current whereas the propagation velocity decreases with decreasing current.

3.2. Burn-out time

As the time passes, the maximum temperature of the normal zone increases with the ‘hot spot’ localised in a region between 30 mm to 50 mm from the top end. The time to reach a predefined temperature; say 240K may be expressed as the burn-out time, which is a reasonable measure of the survival time of the LHC leads at the quench current. Figure 4 shows the burn-out time as a function of the transport current set as the quench current of different top end temperature (solid circles). From the figure, the burn-out time increases with decreasing current as expected. Figure 4 shows the quench behaviour for a constant top end temperature of 85K and current above the quench current corresponding to the 85K (triangle symbols). In this case, the burn-out time is shorter, as the transport current increases above the quench current. It is important to emphasis that longer burn-out times are expected for the hybrid current leads since these leads are cooled using self generated helium vapour, whereas our experiment was carried out in an adiabatic condition and without any vapour cooling. With optimisation, the LHC 13000 A current leads can survive up to 120 seconds after quench is detected. For the AMSC tape with a higher critical current, the burn-out time was 7 seconds without a stainless steel substrate and 20 seconds with stainless steel substrate. The top end temperature of the AMSC tape was maintained at 100K and the conductor was energised with 45A. These results indicate that the stainless steel substrate improves the stability of the HTS section. Furthermore, it shows that the burn-out time following a quench not only depends on the boundary conditions but also on the type of the conductor.

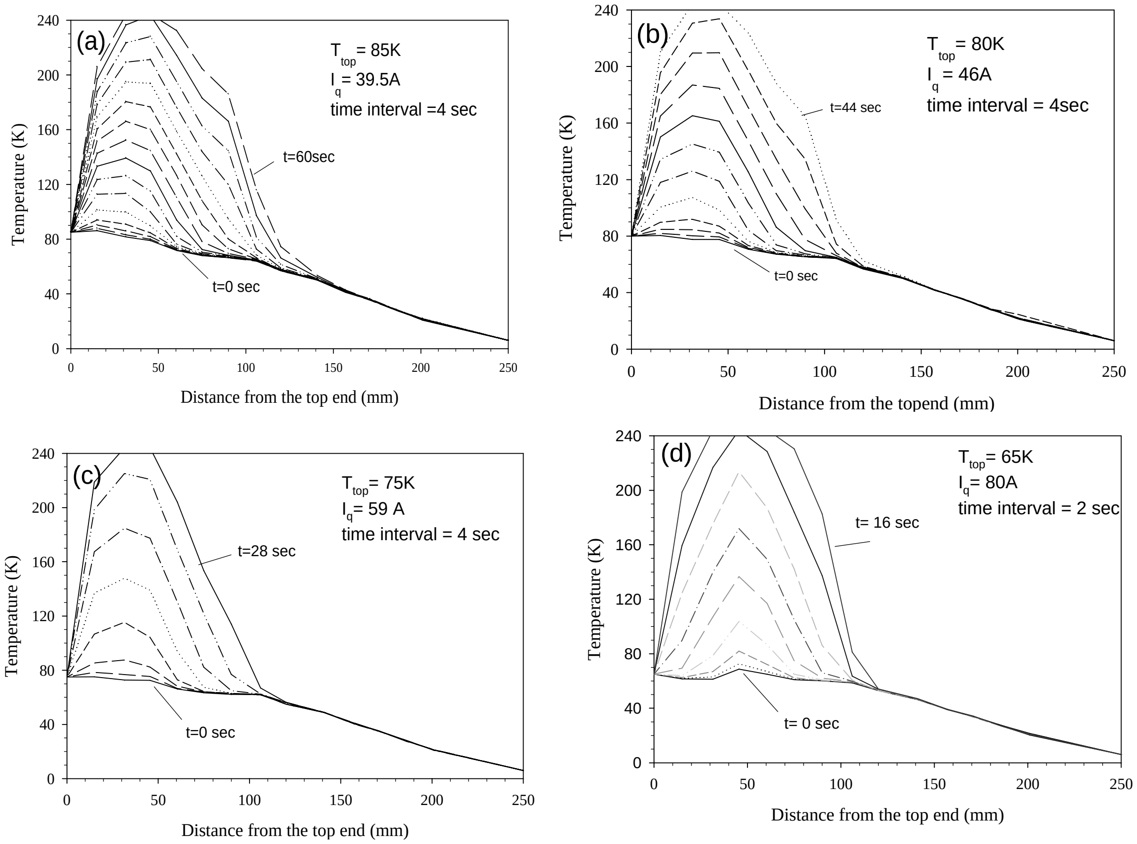

Figure 3. Temperature distributions across the HTS stack at different time intervals and at the quench current. a) T_{top}=85K, I=I_q=39.5A, b) 80K, I=46A, c) 75K, 59A and d) 65K, 80K.

3.3. Quench Propagation Velocity

The evolution of temperature profiles shown in Figure 3 highlights the rate of expansion of the front of the normal zone, which can be expressed in terms of quench propagation velocity. Since the normal zone increases its maximum temperature as it propagates, the propagation front is different from that described for LTS superconductors [5]. We measured the propagation velocity at two different locations on the normal zone front. The first location is at 2K above the steady state temperature profile along the conductor, which represents the excrusion of the tapes deviation from the steady state. The second location is at the ‘sharing temperature’ given by the Ic(T) characteristics of the superconducting tape shown in Figure 2. The length of the normal zone as a function of time for various conditions is shown in Figure 5. The results suggest that for the same operating condition, the slope of the profile is independent of the criterion used. Apart from the onset, linear trends were obtained indicating a constant propagating velocity at a particular operating condition. The onset of these profiles may be seen as the initiation time to develop the normal zone. The propagation velocities as a function of quench current were determined and presented in figure 5 (insert). The figure shows that the propagation velocity increases with increasing quench current.

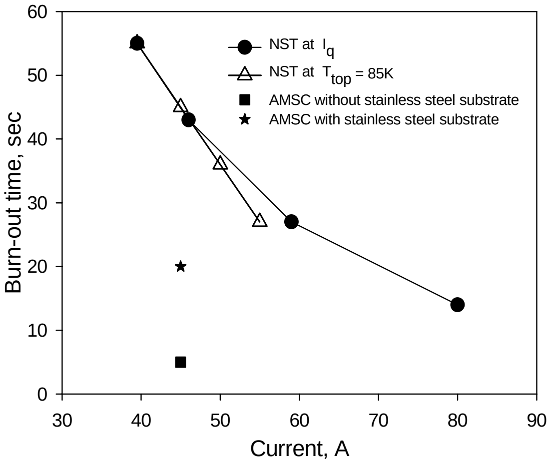

Figure 4. The HTS lead burn-out time

Wilson M. [5] derived an analytical equation for the propagation velocity in an adiabatic condition as;

$$U = \frac{J}{\gamma C}\sqrt{\frac{\rho k}{(T_1 - T_o)}}$$

The propagation velocities for various current densities (J) were calculated using the equation above and presented in Figure 5 (insert). In the equation, the thermal conductivity (k) is mainly dominated by the thermal conductivity of the silver alloy sheath (200 *W/m*K) [4]. The overall specific heat (*C*) was calculated by attributing the total thermal mass (stainless steel and AgAu) to per unit of the HTS tape.

The specific heats of the stainless steel and the AgAu sheath used in this study are 300 *J/kg K* and 200 *J/kgK* respectively. The density (γ) of the stainless steel is 7800 kg/m^3 and the electrical resistively (ρ) of the AgAu sheath is taken as $1.5 \times .10^{-8}$ *Ω.m*. The average temperature between the quench initiation temperature (T_g) and the maximum temperature of the normal zone (T_{max}) is T_1, which increases with time. T_g can be assumed to be equal to the top end temperature, whereas T_o is the base temperature (cooling temperature) and is the steady state temperature of the HTS section in our experiment. In other words, it is the intersection points of the normal zone front (figure 2) with the steady state temperature of the conductor. The estimated propagation velocity as a function of quench current is presented in Figure 5 (insert). Due to the low thermal conductivity of the stainless steel, a period in the region of 3 seconds is needed to reach thermal equilibrium with the tape. Consequently, the cross sectional area of the stainless will not fully contribute to the overall specific heat (*C*) and may need a scaling factor. Nevertheless, the theoretical propagation velocity seems to be in partial agreement with the measured values as it can be seen in Figure 5. Further investigations are required to refine this model for accurate predications.

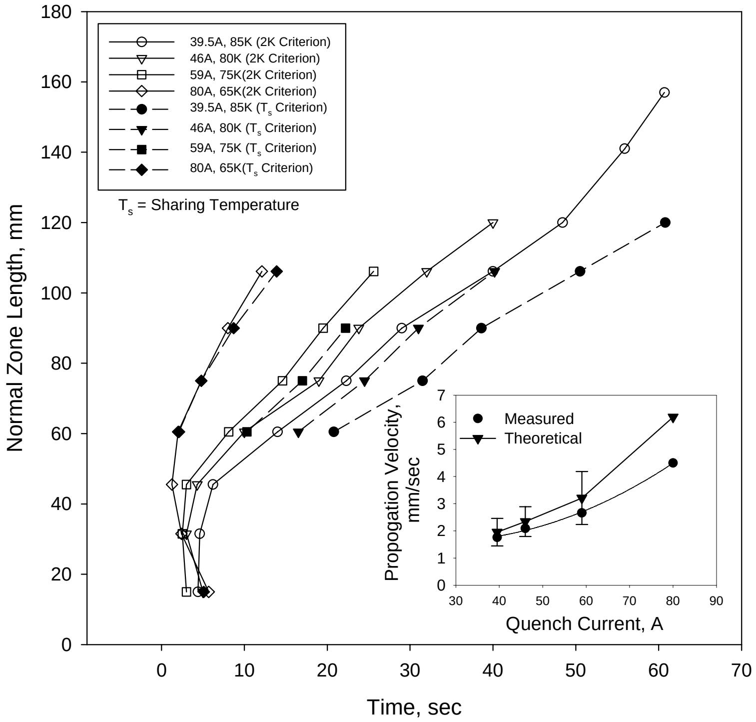

Figure 5. The normal zone length with time. (Insert: propagation velocity as a function of quench current)

4. Conclusions

A cryogenic test rig was designed, manufactured and set-up in order to simulate adiabatic quench propagation in composite HTS current leads. The test samples were produced in a similar way to that used by CERN for their hybrid current leads. The results show that the quench current increases with decreasing top end temperature. The time required to reach 240K decreases with increasing quench current, but seems to depend on the tape properties. Further experimental investigations will be needed to determine the burn-out time for a particular HTS tape. The normal zone seems to be initiated at the top section of the HTS lead which is a typical response associated with adiabatic conditions and fixed end temperatures. The front of the normal zone travels towards the low temperature end at a constant rate which depends on the boundary conditions, the HTS tape properties and the quench current. Nevertheless, it seems that the normal zone does not cover the entire length. The propagation velocities were determined using two criterions, with good agreement for both. The heat capacity of the stainless-steel plays a significant role in stabilising the HTS section and in reducing both the burn-out time and propagation velocity.

5. References

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