Thermal stability and quench propagation in a cryocooler-cooled pancake coil of BI-2223 tape operating between 35K and 65K

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A cryostat for thermal stability and quench propagation studies of HTS pancake coils has been constructed with an operating temperature range between 35K and 65K. The transient thermal response of a test coil to an applied energy pulse has been measured and the minimum energy needed to initiate a quench is presented as a function of temperature and heater length. It has been observed that a normal zone can be formed with a maximum temperature below T_C. The radial normal zone propagation (NZP) velocity is also presented as a function of temperature.

INTRODUCTION

The thermal stability and quench propagation characteristics of HTS coils are important considerations when designing and operating HTS magnets and machines. The minimum energy needed to initiate a quench for HTS coils has been shown to be in the order of joules [1,2]. Despite the high stability of HTS coils their response to transient thermal disturbances must be better understood so that suitable design can be made for quench protection [3].

The concept of a minimum propagating zone (MPZ) was first proposed by Wipf and Martenelli [4], it is a measure of how sensitive a superconductor is to applied energy pulses [5] and has been successfully used to describe the thermal stability of LTS magnets. If a disturbance causes a normal zone to form in a coil with a size greater than the MPZ the normal zone will propagate and the coil will quench. The analysis of the formation and propagation of a normal zone in a HTS coil is complex because a quench occurs over a wide temperature range where the properties of the coil composite are highly temperature dependent. This work investigates the formation and propagation of a normal zone in a 38 turn Bi-2223 pancake coil operating between 35K and 60K.

EXPERIMENTAL

A cryostat for thermal stability and quench propagation studies of HTS pancake coils has been constructed, as shown schematically in Figure 1 and detailed in Table 1 respectively. The pancake coil was cooled at its inner and outer boundaries by conduction via copper thermal links which were thermally anchored to the cold-head of a single stage GM cryocooler. Two small liquid nitrogen vessels located in the vacuum space were used to provide cooling for the radiation shield and AuAg sheathed HTS current leads, and acted as current leads between room temperature and 77K. The current leads were tested up to 300A with the temperature of the cold-head remaining constant at 30K over this current range.

The pancake coil was wound on a thin cylindrical copper former fixed to a Tufnol inner ring using NST PbBi-2223 tape and the copper was used as one of the current terminals. Copper tabs to be used for temperature and voltage measurements were soldered to the tape at different positions. A constantan ribbon to be used as a heater was co-wound with the middle turn of the coil. After winding copper sheets were soldered to the outer boundary and the coil was vacuum impregnated with epoxy. Copper-constantan thermocouples and voltage taps were soldered to the copper tabs. The characteristics of the test coil are shown in Table 1.

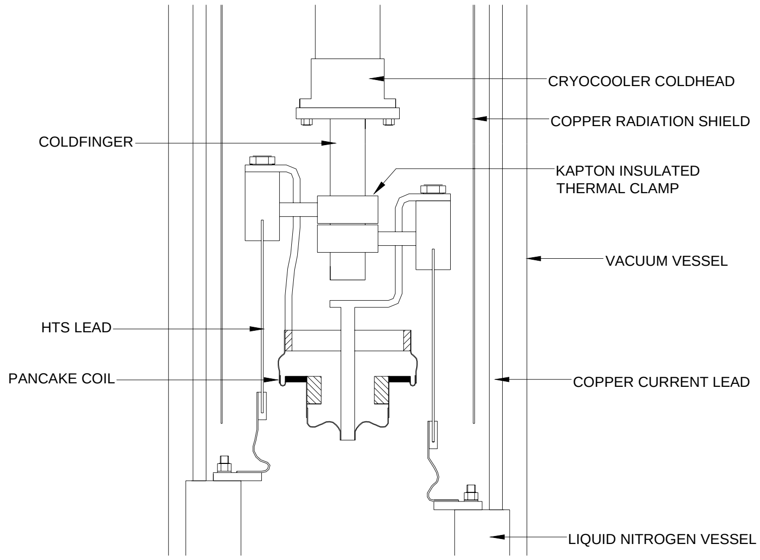

Figure 1, Schematic of part of the cryostat.

Table1. Test coil characteristics

Items	Specifications
Insulation	Fibreglass cloth ~100µm
Former	Tufnol
Number of turns	38
Coil inner radius	30mm
Coil outer radius	45mm
Coil fill factor	~50%
Conductor type	NST 37-multifilamentary Bi2223 tape
Conductor sheath	Outer 0.1MgNi-Ag alloy Inter-filaments: Ag
SC filling factor	27%
Tape dimensions	4.1mm x 0.25mm
I_C	60A at 77K (1µV/cm)

For each test coil boundaries were set at a given temperature between 35K and 60K, and an appropriate transport current was applied that produced an average electric field of 0.7µV/cm across the ends of the coil. For the test results at 60K, 45K and 35K shown in the following, the corresponding transport currents were 87A, 121A and 150A. Upon reaching the steady-state for a given temperature and transport current, transient heating pulses were applied to the different length segments (2.5cm, 8.0cm and 12.5cm) of constantan heater to simulate local and distributed heating. The heat pulses generated by an audio amplifier were a 50Hz sinusoidal wave modulated by a square wave pulse lasting about a second. The transient thermal and electrical response of the coil was recorded using a 32 channel amplifier and data acquisition system. The energy of the heating pulses was increased gradually until a runaway quench was induced. The current supply was programmed to cut out once a set voltage across the quenched coil was reached.

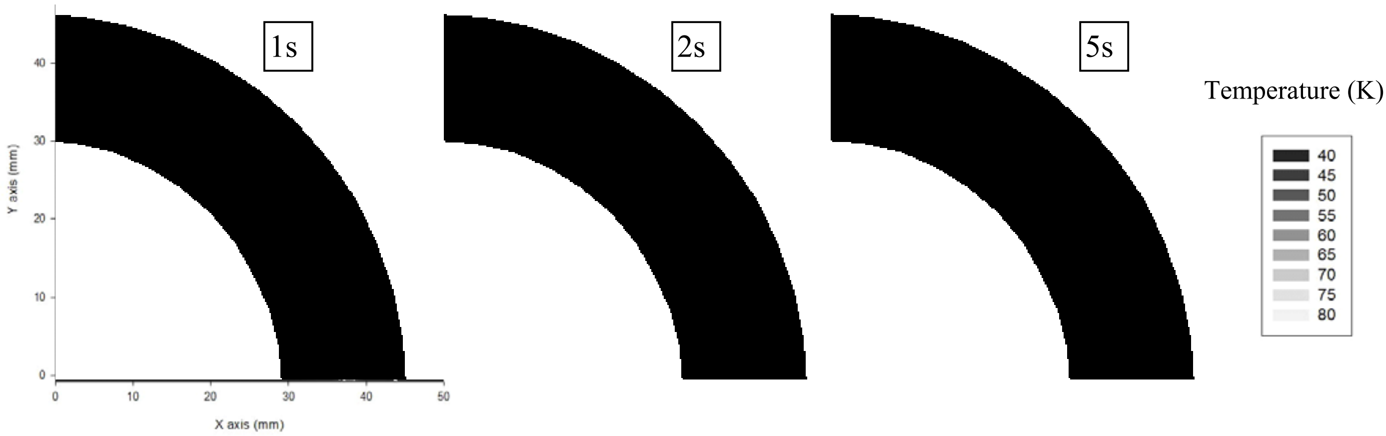

Figure 2 Evolution of the temperature distribution in ¼ of the coil at 35K

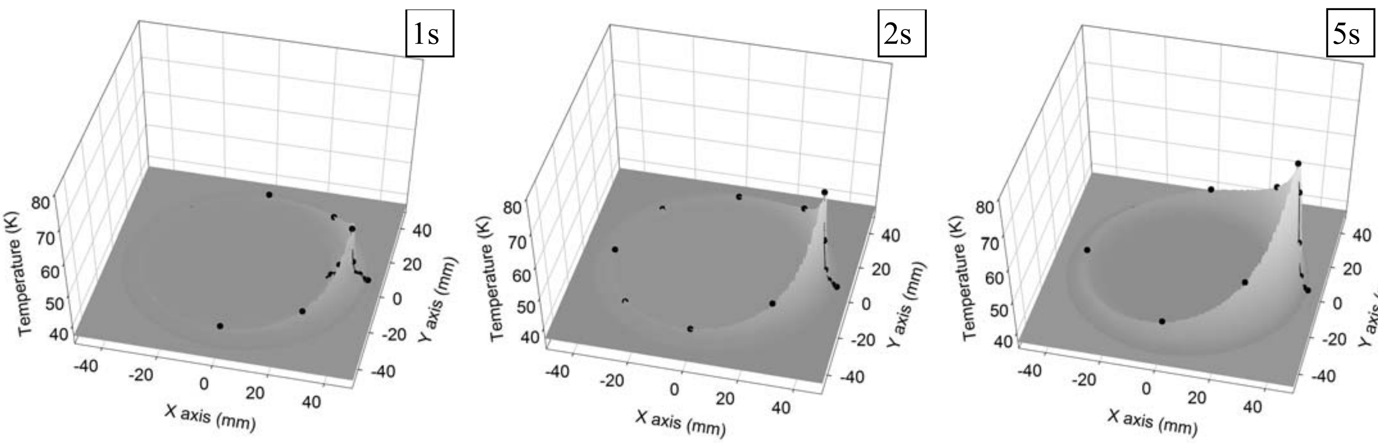

Figure 3. Evolution of the temperature distribution in the entire the coil at 35K (●=Measured data points).

RESULTS AND DISCUSSION

Normal zone growth and propagation
Contour maps of the coil temperature distribution after each heat pulse were obtained using the 18 differential thermocouples distributed across the coil. Figure 2 shows a set of examples at 1s, 2s and 5s after a heat pulse was applied to the coil operating at 35K. In Figure 3 the same maps are presented as a surface distribution with the positions and measured temperatures of thermocouples shown at the same time. Such maps should be used only as visual aids for the qualitative behaviour of propagating normal zone. For the case shown in Figure 2-3, a well defined normal zone can be seen to grow and propagate in the radial and tangential directions. As expected, the normal zone is much narrower in the radial direction than in the tangential direction due to the anisotropic thermal conductivity of the coil.

Figure 4 shows the temperature responses at 60K of thermocouple T6 located at the centre of the heater, and thermocouple T5 located 3 turns away along the same radial direction. It can be seen that for a heating pulse of 13.7J T6 reached a maximum temperature of 80K followed by a full recovery. For a heat pulse of 14.2J, T6 shows the temperature rising within 3s to 81K and keeping almost constant for 8s, during which the temperature at T5 increased steadily to a same temperature of 82K. Sharp temperature increase followed after this point, indicating a classic quench event with the normal zone reaching the size of minimum propagation zone (MPZ).

A constant maximum temperature T_Q (Figure 4) signifies a well defined uniform normal zone temperature which increases very little during its growth to MPZ. Consequently T_Q can be regarded as the quench temperature. It is significant that T_Q is significantly below the critical temperature T_C = 110K, even for coils operating at 60K. The reduction of quench temperature from T_C to T_Q leads to a smaller current sharing regime with the quench of coil before full current sharing by the normal matrix, hence reduces stability of such HTS coils. The quench temperature T_Q for 35K and 45K were found to be 68K and 76K respectively.

Minimum energy
The minimum energy at 35K needed to initiate a quench in the coil was obtained as a function of heater length at various temperatures (Figure 5). It can be seen that the minimum energy to quench the coil increases with the length of the heated section, suggesting a smaller MPZ. The conventional minimum energy for a point disturbance was estimated using the value extrapolated to zero heater length shown as a function of temperature in the inset of Figure 5. The increase of minimum energy with temperature is expected due to the temperature dependent heat capacity of the coil composite. The measured values for the minimum energy are consistent with previous work [1,2] and indicate a high level of stability to transient disturbances.

Propagation velocities
The measured temperature profiles at 35K in the radial direction shown in Figure 6 highlights the

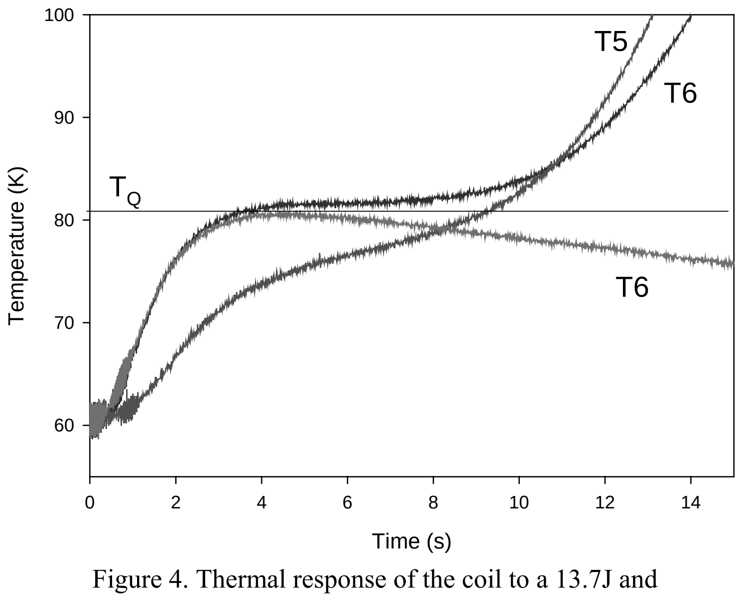

Figure 4. Thermal response of the coil to a 13.7J and 14.2J energy pulse over a 2.5cm heater length at 60K

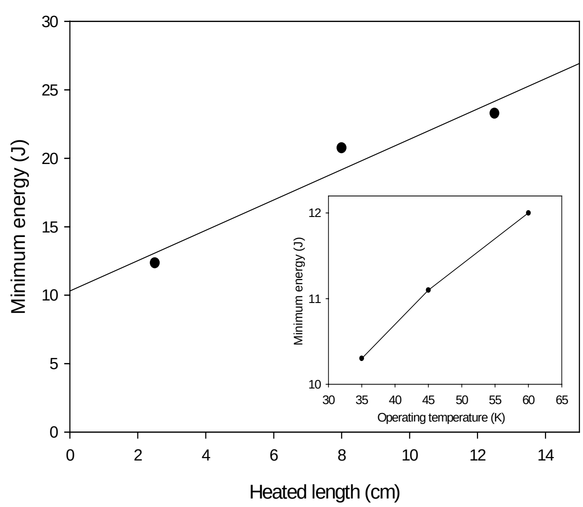

Figure 5. Minimum energy as a function of heater length and temperature

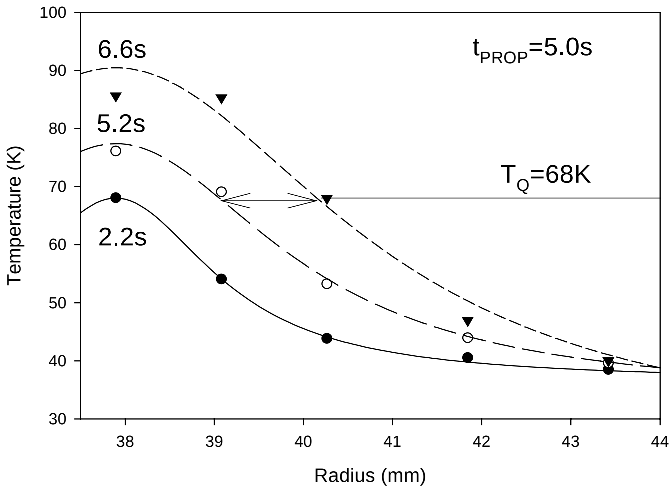

Figure 6. Propagation of a normal zone created by a 2.5cm heater length at 35K

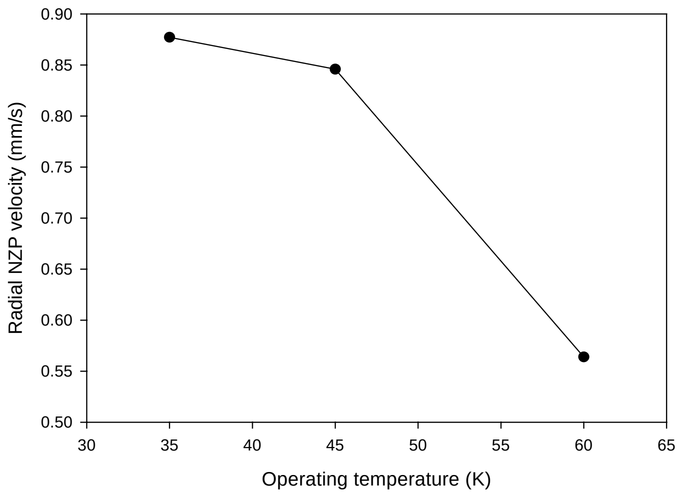

Figure 7. Temperature dependence of the radial NZP velocity

evolution of the propagating form of a normal zone. The radial normal zone propagation (NZP) velocity is obtained at T_Q for each operating temperature and shown in Figure 7. A radial NZP velocity about 0.5-0.9cm/s between 35K and 60K is consistent with previous measurement [2,6]. The observed increase of the NZP velocity with decreasing temperature is due to the increase in the current density of the superconductor and decrease of the heat capacity of the coil composite at lower temperatures. Due to the low radial NZP velocity the normal zone did not propagate far towards the coil boundaries before the temperature of the normal zone began to rise rapidly and the current supply switched off. Therefore the results presented here are consistent with the adiabatic assumption of the classic quench theory.

CONCLUSION

The formation and propagation of a well defined normal zone has been observed in a HTS coil. The maximum temperature of the initial normal zone (T_Q) has been shown to be well below the critical temperature T_C of the superconductor. The lower normal zone temperature $T_Q<T_C$ means that the temperature range for current sharing during normal zone formation is reduced. Less energy is therefore needed to raise the coil temperature to T_Q instead of to T_C. The minimum energy was measured and found to increase as the length of the heated section and operating temperature increased. The propagation of the normal zone was analysed by calculating the radial NZP velocity, which decreases with increasing operating temperature. Both the minimum energy and radial NZP velocity were found to be consistent with previous work.

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