# Boiling heat transfer to liquid nitrogen pool from Ag sheathed PbBi2223 tapes carrying over-current

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Measurements were carried out on boiling heat transfer to a liquid nitrogen pool due to self-heating of Ag sheathed PbBi2223 tapes with increasing over-currents up to 300A, focusing on its difference from increasing heat flux in conventional heated surfaces. Large spontaneous oscillations of the surface temperature were observed and attributed to the interplay between the activation/deactivation of nucleate boiling and the highly non-linear heat generation of the superconductor as a function of temperature. Two distinct steady-states of 8K and 3K superheating were also found for samples carrying 300A depending on the current cycle history.

## INTRODUCTION

The significant enhancement to the performance of high temperature superconductor (HTS) composites, has lead intensified research, development and implementation of their applications in power devices, applications such as motors, transformers, cables, fault current limiters and current leads. Although cooling by cryocoolers can be of great benefit in certain cases, some of these devices are designed to operating in a liquid nitrogen ($LN_2$) pool. There is however little data available [1, 2] on heat transfer to $LN_2$ to HTS under direct heating by an over-current above the critical current. The distinction between direct heating of superconductors by transport over-current and heating from conventional heater is the focus of the present work. Above the critical current $I$c, the heat generation in a superconducting composite can vary sharply by several orders of magnitude with both current and temperature, due to its highly nonlinearly resistivity $\propto (I/I\text{c})^n$ ($n \gg 1$), the strong temperature dependence of $I$c in the vicinity of $T_C$, and the gradual current sharing with the normal matrix with increasing temperature. In contrast, resistivity of a conventional heater is independent of current and can be considered constant for pool boiling of up to 15K superheating. The unique nonlinear heat generation of superconductors is expected to result in unconventional heat transfer characteristics, as has been shown in [2], where a large fluctuation of heat generation was observed.

It should be noted however that previous works have been limited to a small heat flux due to low critical current of the superconductor used and lack of accurate temperature measurement. In this paper high current BiPb2223 tapes (AMSC 115A) were used. Simultaneous measurements of voltage and temperature were made to determine local value to heat generation and surface superheating with increasing over-current up to 300A. The time dependence of power fluctuations was recorded at 100Hz to investigate the dynamics of the heat transfer process.

## EXPERIMENTAL

Four BiPb2223 Ag sheathed tapes ($I$c = 115A) were mounted side by side on a base of glass fibre composite to form a meander. Copper current pads recessed into the base and soldered to the tape ends make the meander continuous, and several pairs of voltage taps were soldered at a separation of 10mm along the tapes. Copper-constantan thermocouples were soldered directly to the superconductor between the voltage taps and connected to thermocouples immersed in $LN_2$ to form differential thermocouples. The tapes were potted with the voltage taps and thermocouples face-down into a recess in the base, in order to ensure a smooth boiling surface and thermal isolation of the thermocouples from the cryogen. The heat leak through the base and wires is negligible. The assembly was mounted vertically in a $LN_2$ bath, simultaneous temperature and voltage data was taken using voltmeters whilst the current, (constant current mode), was incremented from zero to the maximum value then decreased back to zero. The heat generation per unit area by the tape is calculated from the voltage current product. Heat transfer stability was recorded at 100Hz using a high resolution Analogue to Digital data logger. A parallel shunt was used to allow stable over-current up to 300A and prevent sample burn-out upon transition to film boiling.

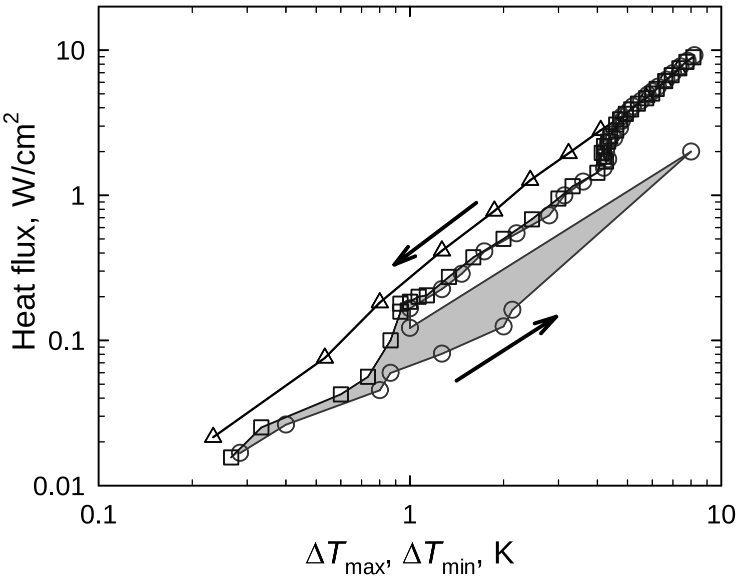


Figure 1 Heat flux vs. surface superheat of a superconducting tape carrying over-current in a $LN_2$ pool

## RESULTS

Steady-state characteristics of heat transfer to $LN_2$ from superconductor directly heated by over-current

The surface superheat $\Delta T = T_S - T_{LN}$ and the corresponding dissipative voltage $V$ were measured with increasing transport current $I$. The result shown as a conventional plot of heat flux ( $\propto V{\cdot}I$ ) vs. $\Delta T$ in Figure 1. With increasing current up to 200A there is a large fluctuation of surface temperature, and both the maximum (○) and minimum (□) $\Delta T$ are shown in Figure 1, where the enclosed grey area indicate the range of fluctuation. Further increase of current above 200A leads to a consistent superheat above 4K with the onset of nucleate boiling, and diminishing temperature fluctuations. Upon reducing current from 300A, surface temperature (△) became well defined as the surface remains activated, and an enhanced heat transfer was found.

As shown clearly in Figure 1, there is no unique correspondence between the heat flux and surface superheat over a large range of current above $I$c. As mentioned previously, this is most likely related to the highly nonlinear heat generation of superconductors as a function of both current and temperature. In this case the heat transfer is better understood with the transport current as the primary variable. To this end, superheat $\Delta T$ and dissipative voltage $V$ are shown as functions of current in Figure 2a-b respectively. It becomes clear that the large range of temperature

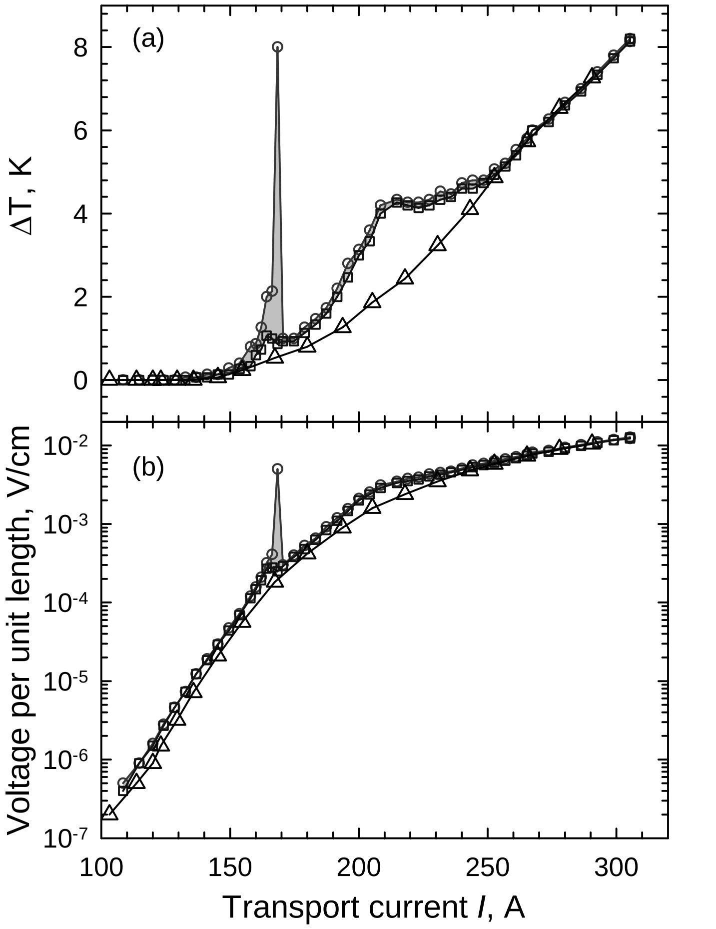


Figure 2 Surface superheat (a) and dissipative voltage (b) of a superconducting tape as a function of over-current in $LN_2$

fluctuation occurs above 150A when the dissipative voltage is above 0.2mV/cm, corresponding to about $0.1W/cm^2$. In the particular case shown in Figure 2, there was a large temperature increase to 8K above the saturation temperature with a transient heat generation of $2W/cm^2$. Such a large superheat led to a partial activation of nucleate boiling, which offers much enhanced heat transfer and consequent sharp reduction of superheat. The superheat is further reduced by large reduction in the heat generation. Such an interplay between the superheat and heat flux is unique to superconductors and results in a quick reduction of activated sites. The temperature fluctuation shown in Figure 1 is thus attributed to the cycle of activation and deactivation in the normally non-activated regime for conventional heated surfaces.

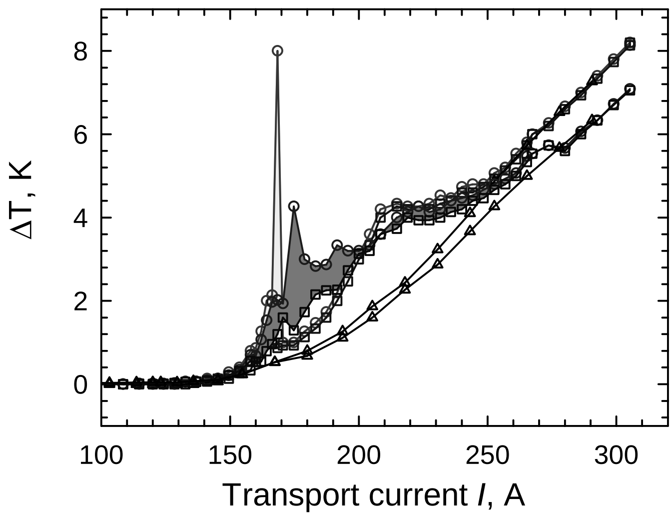


Figure 3 Surface superheat as a function of over-current from two separate locations as an indication of the randomness of the temperature oscillation

It should be noted that the temperature measurement here was very localised, hence the results shown in Figure 2 only indicate the existence of large temperature excursions and does not represent the random variation with location. In Figure 3, $\Delta T$ from a different thermocouple located at a different spot showed a lesser degree of fluctuation but a more extended range (dark grey area) to higher current, possibly due to lack of partial activation seen in the other measurement.

According to Figure 2-3, the transition to nucleate boiling occurs between 200A and 250A, where there is little increase of $\Delta T$ with increasing current. This is because the surface is still overheated compared to activated nucleate boiling (△) upon reducing current from 300A.

<u>Spontaneous behaviour of heat transfer to $LN_2$ from superconductor directly heated by over-current</u>

Further investigation on the dynamics of temperature fluctuation was carried out by time-resolved simultaneous measurement of superheat $\Delta T(t)$ and dissipative voltage $V(t)$. Figure 4(a) shows the time history of $\Delta T$ and $V$ for a typical run with ramping current from 180A to 209A with 1A increment. With increasing current to 195A, the superheat increase steadily to 5K with fluctuation in the range of 0.5-1.0K, while the dissipative voltage crept up from 1mV/cm to 3mV/cm. At about 195A, an event of activation occurred with a sharp drop of $\Delta T$ by about 1.5K. The activation reduces gradually, even with an increasing heat flux at further increase of current, and the superheat reach 5K again at 209A. With a constant current of 209A, the superheat suddenly dropped by 3K after 500s following another spontaneous incident of activation. The heat generation is reduced from $3W/cm^2$ to about $1W/cm^2$. Consequently a cycle of activation-deactivation-activation is completed. In addition to the large scale activation events, the fluctuations below 195A can be understood in a similar manner. Figure 4(b) shows the detail of a 2 minutes time history of such smaller oscillations at 190A. A strong correlation between the superheat and the voltage is clearly evident.

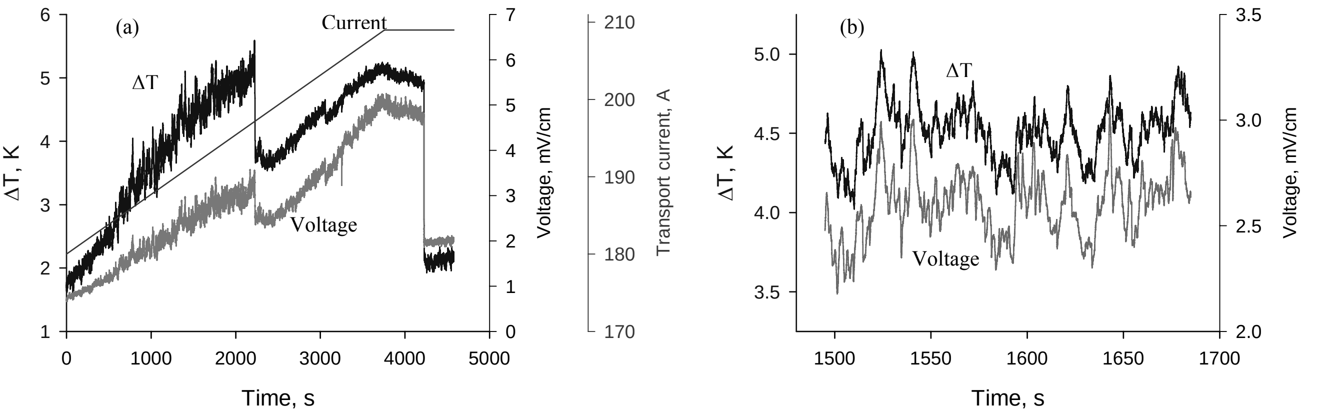


Figure 4 Time history of $\Delta T$ and $V$ with increasing current from 180A to 210A (a) and at constant current of 190A (b)

With a larger current increment of 5A, an event of rapid superheating to 8K followed by local activation is captured, as shown in Figure 5(a). The detailed history of the event shown in Figure 5(b) indicates that the large superheat is established with 12s following a 5A current increment. The cooling by activation of boiling is very steep with an initial rate of about 3K/s. While maintaining a constant current of 190A, the superheat in the bulk liquid was removed by introducing vigorous boiling in the pool. As a result the surface of the superconductor became fully activated due to an increase in the effective surface superheat. It is noted that $\Delta T$ remained virtually constant at 3K with further increase of current to 215A. The voltage measured during this period (Figure 5(a)) corresponds to isothermal heat generation of the superconductor in the over-current regime and can be used for constructing the heat generation as a non-linear function of temperature and current.

It is clear from Figure 5(a) that with full activation of the boiling surface, the superheating and heat generation of the superconducting tape can be much lower than the sae of partially activated surface (Figure 3). To further highlight such a difference, Figure 6 shows the heat transfer characteristics upon reducing current from 300A with and without full activation. It is clear that a full activation led to a reduction by 4K in the superheat $\Delta T$ which remains lower than not fully activated surfaces for current down to 200A. Such a cooler condition is much desirable during recovering from over-current. It remains a challenge to maintain the surface activated at such small superheat.

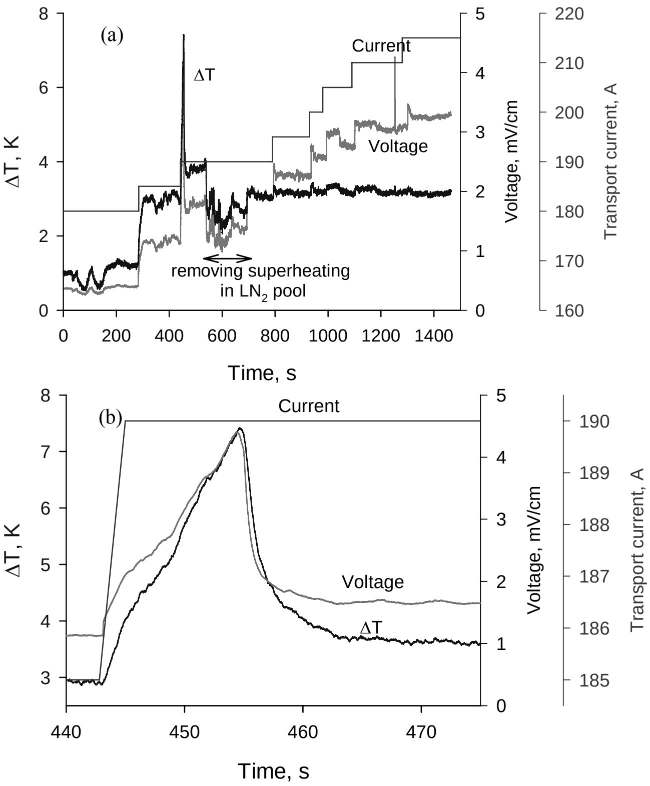


Figure 5 Time history of $\Delta T$ and $V$ with large step increment of current (a) and the details of an activation event

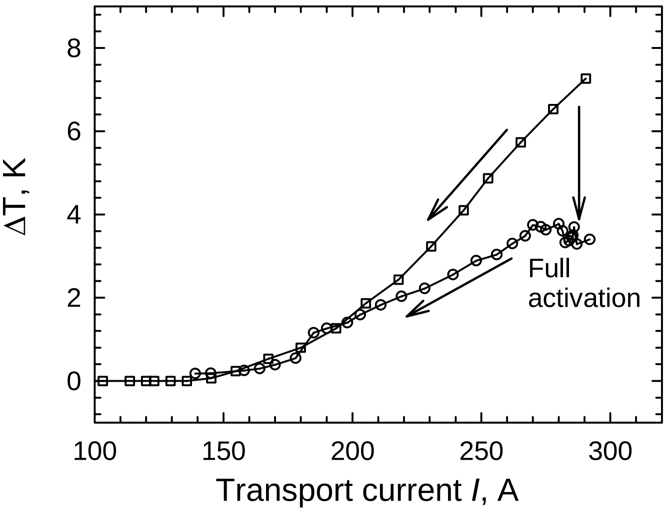


Figure 6 Surface superheat $\Delta T$ as a function of over-current for partially activated and fully activated surfaces

## CONCLUSION

Unique characteristics were found in the heat transfer from HTS Superconductors carrying over-current due to the interplay between the nonlinear heat generation in the superconductor and the activation-deactivation of nucleate boiling at small heat flux. In addition full activation of surfaces results in not only the expected reduction in the superheat, but also an unconventional lower heat flux. Although such an “over” cooled state is desirable for quench recovery, its stability maybe limited due to a larger tendency to deactivate.

## REFERENCES

1. Chovanec, F and Usak, P, Cryogenics **42**, 543 (2002).
2. Skokov V, N, and Koverda, V, P, Cryogenics **33**, 1072 (1993).