The method of measuring the temperature dependence of the critical current of the HTS-2

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Abstract. A new method of measurement of \( I_c(T) \) dependence for the HTS-2 tape is realized. In this method, the metal substrate of the tape is used as both a heater and a thermometer. Index \( n(T) \) was calculated from the measured current-voltage characteristics (CVC). For the tape manufactured by SuperPower Inc. the data of \( n \)-index temperature dependence in the range from 77 K up to 90 K are presented.

1. Introduction
The critical current \( I_c \) is one of the main characteristics of superconductors for their application. There is a lot of data on the HTS-2G critical current measurement at the liquid nitrogen temperature \([1,2]\). But published results on the \( I_c(T) \) dependence at elevated temperatures are much more modest because of the complication in measurement procedure. Cryocoolers are often used for tape cooling \([3]\). In this case, the tape is placed in the vacuum vessel and absence of a heat-exchange gas causes a drawback of the method. Along the tape there is a temperature gradient and local thermometer cannot correctly measure a temperature of long sample. Besides, there is a high probability of the tape's burnout at large currents. In the case of gas or liquid cooling the tape's burnout is less likely but the thermometric problem is still actual. In this paper a new method for measurement of \( I_c(T) \) dependence in the superconducting tapes is proposed.

2. Experiment
A layered structure of the HTS-2 tape is shown in the right part of Figure 1. The superconductive layer (YBCO – 1 \( \mu \)m) is separated by dielectric buffer layers (0.2 \( \mu \)m total thickness) from the substrate (Hastelloy - 50 \( \mu \)m). These layers are covered by protective silver layer (Ag – 2 \( \mu \)m) and stabilizing copper layer Cu (20 \( \mu \)m) at both sides. Being closed at the edges, the copper layer is a single coating.

After removal of copper from the lateral edges, the substrate and the superconducting layer proved to be galvanically isolated but the critical current of tapes at \( T = 77.4 \) K fell down from 114 to 109 A. Probably, that is caused by removing of a portion of the superconductor. After the isolating the metal layers at substrate side can be used as a heating element. The resistance of the Hastelloy layer is several orders higher than that of copper and silver layer \([5]\), so the latter bridges it. If the temperature dependence of Cu-Ag layer resistance \( R(T) \) is calibrated it can be used as a thermometer (hot wire

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method – [4]). Electrical connections of tape are shown on the left side of Figure 1. In this structure the thermometer is placed along the tape surface. This thermometer is convenient in the temperature range from 50 to 250 K. We found that $R(T)$ dependencies for two pieces of the tape are practically linear in the range of 75-100 K, and their slopes $dR/dT$ differ by less than 5%.

![Figure 1](image1)

**Figure 1.** (left side) the CVC measurement diagram: 1 – the thermometer current leads, 2 – the thermometer voltage contacts, 3 – the superconductor voltage contacts, 4 – the superconductor current leads; (right side) the tape layers structure.

The thermometer readings are consistent with the superconducting layer temperature if heat flux is small. Indeed, the temperature difference $\Delta T$ between the superconductor layer and the thermometer depends on the transverse heat flux $q$ as

$$\Delta T = q \left( \frac{h_{Hast}}{\kappa_{Hast}} + \frac{1}{\kappa_{surf_{buf}}} \right)$$

where $h_{Hast}$ - the thickness, $\kappa_{Hast}$ - thermal conductivity of the Hastelloy layer, $\kappa_{surf_{buf}}$ - thermal conductivity of the buffer layer per unit area. According to [5, 6] $\kappa_{Hast} = 0.06$ W / cm $\cdot$ K, $\kappa_{surf_{buf}} = 270$ W / cm$^2$ $\cdot$ K and $h_{Hast} = 50$ μm. So when the transverse heat flow is less than 1 W/cm$^2$, the temperature difference between the superconducting layer and the thermometer does not exceed 0.1 K.

![Figure 2](image2)

**Figure 2.** (■) – the tape surface overheat over the nitrogen boiling temperature and (―) – the difference between temperatures of YBCO layer and thermometer.
Conventional method to determine $I_c$ is direct measurement CVC in liquid nitrogen. The dependencies of the temperature jump on the tape's surface and interlayer temperature difference (YBCO – thermometer, $\Delta T$) on transverse heat flow are shown on the Figure 2. When the surface temperature exceeds the boiling point of liquid nitrogen up to 3 K the transverse heat flow causes negligible temperature gradients in the cross section of the tape. In the case of overheating the surface of about 5 K the boiling regime changes. At higher temperatures the heat flux substantially distorts the temperature distribution.

At temperatures above 80 K (up to $T_c$) measurements were carried out in evaporated nitrogen gas. In this case, the measuring cell was placed in Styrofoam box turned upside-down and filled with cotton wool to prevent the convective flow of nitrogen gas. In such an arrangement, known as the "inverted Dewar" [7], the temperature field is fairly uniform, and substantial overheating above the nitrogen boiling temperature is achieved with small heating power. On the other hand, the possibility of tape burnout significantly reduced in the ambient gas compared to vacuum.

3. Results

Figure 3 shows the results of measurement of current-voltage characteristics of the tape at various temperatures in ambient gas. The voltage generated by the thermoelectric power was excluded during the processing the CVC.

![Figure 3. The HTS current-voltage curves at different temperatures. Inset – one of the curves in logarithmic scale.](image)

Using an electric field level 1 $\mu$V/cm as the criterion of the critical current – the $I_c(T)$ dependence was determined. As shown in Figure 4, this dependence is linear and slightly flattens in vicinity of the critical temperature. It confirms well the known data [3, 8].

As a rule, the CVC is described by a power dependence

$$V = V_0 \left( \frac{I}{I_c} \right)^n$$

where $n$ is the the CVC index [9]. Linearity of CVC in a logarithmic scale, presented in the inset of Figure 3, demonstrates a good agreement with the CVC power-law approximation. Therefore several CVCs obtained at different temperatures allow to obtain $n(T)$ dependence. This dependence is shown in
Figure 4. In the temperature range 78-86 K the CVC index remains practically unchanged. As the temperature increases further up to $T_c$ the sharp decrease in $n$ is observed.

The superconducting transition of $R(T)$ is also shown in Figure 4 as an illustration. For the measured tape the critical temperature, corresponding to $R = 0$, is equal to 89.8 K.

Figure 4. The temperature dependencies of critical current (■), $n$-index (▲). The left part corresponds the measurement in liquid nitrogen, the right part – in ambient gas.

4. Conclusion
An original method of CVC measurement with precise temperature control was developed for the HTS-2 tape. In this method the normal layer was employed as both a heater and a thermometer.

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