pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.22, No.4, (2020), pp.14~19
https://doi.org/10.9714/psac.2020.22.4.014

Stability and normal zone propagation in YBCO tapes with Cu stabilizer depending on cooling conditions at 77 K

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(Received 4 November 2020; revised or reviewed 28 December 2020; accepted 28 December 2020)

Abstract

Here we present the comparative experimental study of the stability of the superconducting state in 4 mm YBCO tapes with copper lamination against local heat disturbances at 77 K. The samples are either directly cooled by immersing a bare YBCO tape into a liquid nitrogen pool or operate in nearly-adiabatic conditions when the tape is covered by a 0.6 mm layer of Kapton insulation. Main quench characteristics, i.e. minimum quench energies (MQEs) and normal zone propagation (NZP) velocities for both samples are measured and compared. Minimum NZP currents are determined by a low ohmic resistor technique eligible for obtaining *V - I* curves with a negative differential resistance. The region of transport currents satisfying the stationary stability criterion is found for the different cooling conditions. Finally, we use the critical temperature margin as a universal scaling parameter to compare the MQEs obtained in this work for YBCO tapes at 77 K with those taken from literature for low-temperature superconductors in vacuum at 4.2 K, as well as for MgB_2 wires cooled with a cryocooler down to 20 K.

Keywords: YBCO tape, YBCO coated conductor, stability

1. INTRODUCTION

The development of high temperature superconducting (HTS) devices based on YBCO tapes requires exact information about the mechanism of normal zone initiation and propagation in coated conductors. Local disturbances of thermal or mechanical origin can distract the superconducting state. The superconducting tape or wire, in this case, is heated up to its critical temperature and transits to the normal state. If the heat transfer to the coolant is higher than the ohmic heat generated within the local normal zone, the superconducting state recovers after a while. However, if the length of the superconductor in the normal state exceeds a critical value, normal zone propagation (NZP) starts. In HTS devices this process must be detected as soon as possible, since it can cause the whole magnet failure, especially if the high magnetic energy is stored in the device.

There are two main parameters for the HTS magnets protection. The first one is NZP velocity. The second one is minimum quench energy (MQE) – the threshold value of the energy dissipated within the superconductor high enough to trigger NPZ. These parameters depend on temperature T_0, magnetic field B_0, and transport current I_t. MQE increases with transport current decreasing. Thus, there is a minimum NZP current (I_m) below which any disturbance can't cause normal zone propagation. In other words, this threshold value determines the region of currents where the stationary stability of an HTS device is fulfilled. Of course, the disturbances causing the superconductor melting of other destructions of its structure are out of consideration.

The determination of the above-mentioned quench characteristics for YBCO tapes drew the attention of scientists worldwide just after the discovery of HTS materials and is still underway. While in early papers the transient heat transfer in liquid nitrogen (LN2) was investigated on platinum films [1] at that time just imitating HTS tapes, today the transient stability of HTS coils wound with commercial coated conductors is under consideration [2].

Quantitative results of even very similar experiments on YBCO tapes stability can vary considerably. Incorporation or otherwise of a normal metal stabilizer in the structure of an HTS tape, cooling conditions onto its surface, the position of thermometers and heaters, all these factors can affect the thermal behavior of the system drastically. Let us list the most representative works of other authors on the subject. In [3] MQEs measured on a (0.091 mm x 8.89 mm) bare YBCO tape at 80.6 K in nearly adiabatic conditions appeared to be equal to (340-205) mJ at $I_t / I_c = (0.5 – 0.9)$ correspondingly, whereas NZP velocities varied from 2.5 mm/s to 7.5 mm/s. In contrast, in [4] 2 mm wide YBCO tapes at 77 K demonstrated considerably lower MQEs of about 9 mJ at $I_t / I_c = 0.75$ inconsistent with the reduction of the sample size.

The presence of a copper stabilizer increases both MQEs and NZP velocities. Thus, in [5] 10 mm wide Cu stabilized YBCO tape at 80 K demonstrated MQEs of about (1-0.4) J and VZP velocities in (4-15) mm/s range for $I_t / I_c = (0.5 – 0.9)$. On the other hand, 4 mm YBCO tape from [6]

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investigated in the same experimental conditions showed MQE = (0.75-0.3) J and NZP velocity of about 15 mm/s at $I_t / I_c = 0.5$.

The authors of [7] evaluated the main quench characteristics of thermally insulated YBCO tapes at 77 K. The experimental NZP velocities appeared to be 2 to 3 times lower than the calculated ones. There was another interesting fact about this work. Despite nearly adiabatic conditions, no quenches were registered at transport currents $I_t / I_c < 0.3$. Even when the heater burned out at dissipating energy of 2.7 J (which was obviously higher than the critical energy of the tape), the superconductivity of the sample remained. Thus, the stationary stability criterion seemed to be fulfilled in the region of small transport currents even for the thermally insulated YBCO tape.

In [8] the quench/recovery process was experimentally investigated for a (4 mm x 0.1 mm) copper stabilized YBCO tape immersed into a liquid nitrogen pool. It was shown that the HTS tape carrying the transport current $I_t/I_c = 0.86$ could withstand a short overcurrent pulse with $I_t = 6 \cdot I_c$ during 6 ms accompanied by the sample overheating up to 500 K. After 7 s the sample recovered its superconducting properties without any degradation.

It becomes obvious from this brief analysis, that the presence of samples' holders, voltage taps, and even thermometers leads to heat leakages. Ideal adiabatic conditions can't be arranged during an experiment. That is why an additional cooling coefficient must be taken into consideration. For instance, in [9] its value was estimated as 0.1 W/(m·K). Even the position of a heater onto the sample surface can affect the obtained results. In [10] it was shown that if a heater was mounted onto the YBCO side of a tape, MQEs were almost two times lower than those initiated with the same heater placed onto the Hastelloy substrate: MQE = (0.7-0.4) J instead of MQE = (1.6-0.6) at $I_t / I_c = (0.5 – 1.0)$ and in (75 - 80) K temperature range.

The goal of this work is to measure the main quench characteristics of commercial 4 mm YBCO tapes with copper lamination depending on the cooling conditions, find a region of transport currents satisfying the stationary stability criterion, and compare our results to those obtained by other groups for different superconductors.

2. SAMPLES

We prepared two experimental samples made of commercial YBCO tapes (4 mm x 0.1 mm x 94 cm) SCS4050 by Superpower [11] with a 25 µm copper stabilizer on each side of the tape – see Table I for details. The samples were mounted on a hard fiberglass mandrel and equipped with local 50 Ohm heaters. The latter were made of a bifilar Constantan wire 15 µm dia in Kapton insulation in the form of a flat spiral with the dimensions (4 mm x 6 mm x 0.065 mm).

Fig. 1 shows the schematic cross-sections of the samples at the location of the heaters. The YBCO side of the tape was faced towards the heaters through the 80 µm layer of thermal paste in both cases.

The bare sample had a free outer surface to ensure the direct contact with LN2.

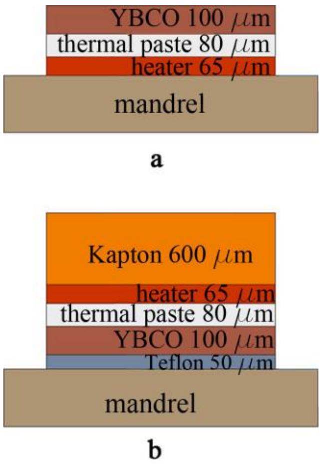

Fig. 1. The cross-section schemes of the YBCO samples at the location of the heaters: a – the directly cooled sample, b – the thermally insulated sample (not to scale).

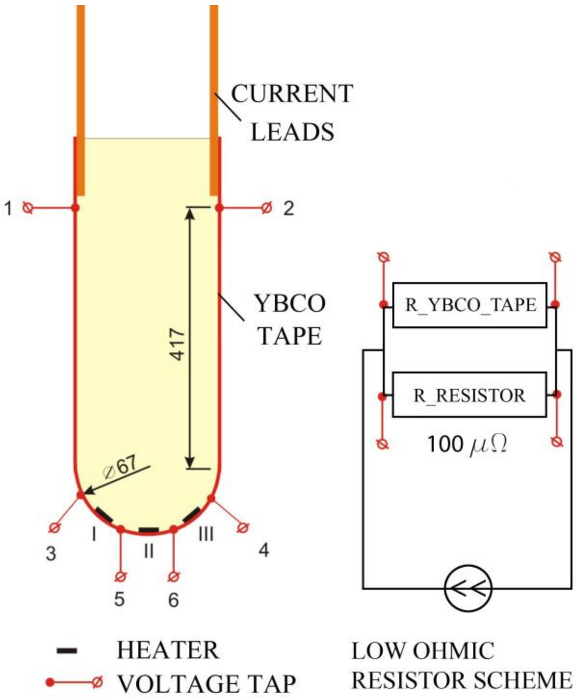

Fig. 2. The schematic view of the test rig. I, III – stationary heaters, II – pulse heater.

TABLE I
PARAMETERS OF THE YBCO SAMPLES.

Sample	Directly cooled	Thermally insulated
Cooling conditions	Free outer surface in direct contact with LN2	Outer surface is cooled by LN2 through a 0.6 mm layer of Kapton insulation
I_c (77 K, self field), A	127	112
HTS tape	SuperPower SCS4050 4 mm x 0.1 mm (50 µm Hastelloy, 2x25 µm copper with RRR=57 on each side of the tape)	

The surface of the thermally insulated sample was additionally covered with a Kapton film 0.6 mm thick on the length of 100 mm. In this case, there also was a 50 µm Teflon layer between the YBCO tape and the mandrel to omit the microchannels for LN2 penetration. The critical currents of the samples measured with 1 µV/cm criterion appeared to be equal to 127 A and 112 A for the directly cooled and thermally insulated samples correspondingly.

3. TEST RIG

During the tests, the insert with the YBCO samples was immersed into a liquid nitrogen pool in the vertical position as it is schematically shown in Fig. 2. Both samples were equipped with 3 pairs of voltage taps made of a thin copper wire 0.12 mm dia. The voltage drop across the whole sample was monitored by the first pair of voltage taps 1 - 2. They were used to determine the minimum normal zone propagation currents. The other two pairs of voltage taps were soft soldered to the Hastelloy substrate of the YBCO tape symmetrically with respect to the heaters 2 cm away from one another. The voltage taps 5 - 6 (installed around the pulse heater II) and the voltage taps 3 - 4 (installed next to the stationary heaters I and III) were used in MQE and NPZ tests to monitor the normal zone propagation process. During the experiments, only one stationary heater was used. The second stationary heater was considered as a spare one.

4. RESULTS AND DISCUSSION

4.1. Minimum normal zone propagation currents.

We started the experimental programme with the minimum NZP current (I_m) determination by a low ohmic resistor technique [12]. The method is as follows. The test sample was connected with a low ohmic resistor in parallel – see Fig.2. The resistivity of the latter was adjusted close to the resistivity of the sample in the normal state. During the test, the sample was charged with increasing transport current I_t and simultaneously heated with the heater operating in the stationary mode. While the voltage across the initiated normal zone increases, the total current shares between the YBCO tape (I_t) and resistor (I_r). Sample current I_t correspondingly decreases forming the negative differential resistivity in the V - I curve – see Fig. 3. The process of current sharing stops at a certain value I_m. It corresponds to the moment when the thermal equilibrium between the heat generated within the YBCO tape and the heat transfer to the coolant is achieved. In other words, I_m can be considered as a threshold current defining the stationary stability criterion. Below this current, there are no local heat disturbances that could cause normal zone propagation. Fig. 3 demonstrates the *V-I* curve for the directly cooled YBCO tape in the low ohmic resistor experiments for the two stationary heater power values: 0.1 W and 0.5 W. In this case, the minimum NZP current I_m appeared to be equal (79±1) A or 62% from I_c.

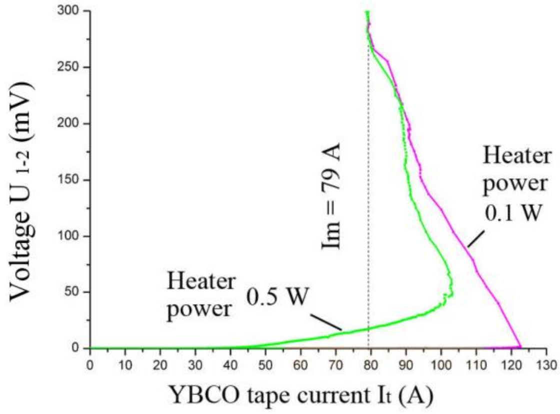

Fig. 3. *V-I* curve for the directly cooled YBCO tape in the low ohmic resistor experiments under stationary heating at two different heater power values 0.1 W and 0.5 W. The dashed line shows the minimum NZP current I_m = 79 A.

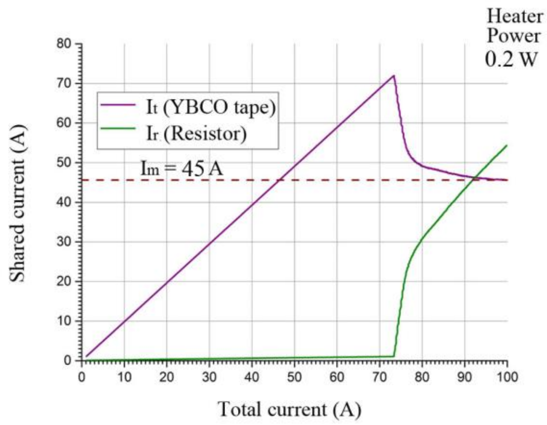

Fig. 4. The process of current sharing between the superconductor (I_t) and the resistor (I_{sh}) at the 0.2 W stationary heating power for the thermally insulated YBCO tape. The dashed line shows the minimum NZP current I_m = 45 A.

In Fig. 4 the results of the same experiments are shown for the thermally insulated YBCO tape as the current sharing process between the superconductor (I_t) and the resistor (I_r) at the heater stationary power of 0.2 W. The dashed line shows the minimum NZP current I_m = (45±1) A. As it was already mentioned above, the ideal adiabatic conditions can’t be arranged. Thus, while describing the normal zone dynamics, I_m can be considered as a cooling coefficient [13, 14].

4.2. Minimum quench energies.

During the MQE tests normal zones were initiated within the samples by a 200 µF condenser discharge at different voltages through the pulse heater with a disturbance duration τ_p = 10 ms. The thermal diffusion coefficient across the sample was estimated as the total time needed to warm up the layer of thermal paste between the heater and the YBCO tape $\tau_L = C{\cdot}d^2/k$ = 21 ms. Here C, k, and d are volumetric heat capacity, thermal conductivity, and the thickness of the thermal paste layer correspondingly.

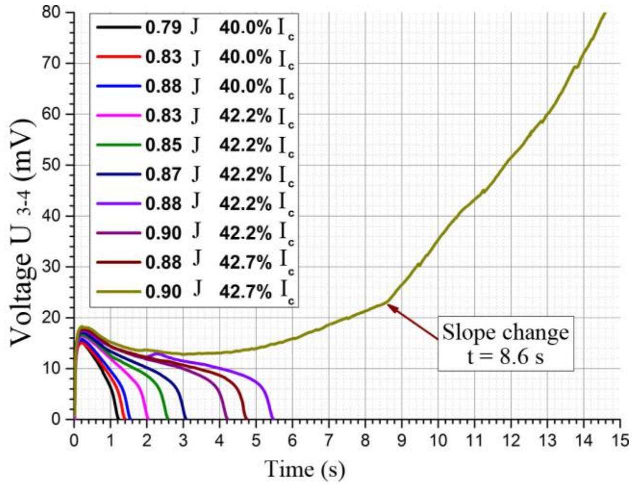

Fig. 5. The process of the normal zone initiation in the thermally insulated YBCO tape as temporary dependencies of the voltage drop triggered by increasing heating pulses at transport currents 45 - 48 A.

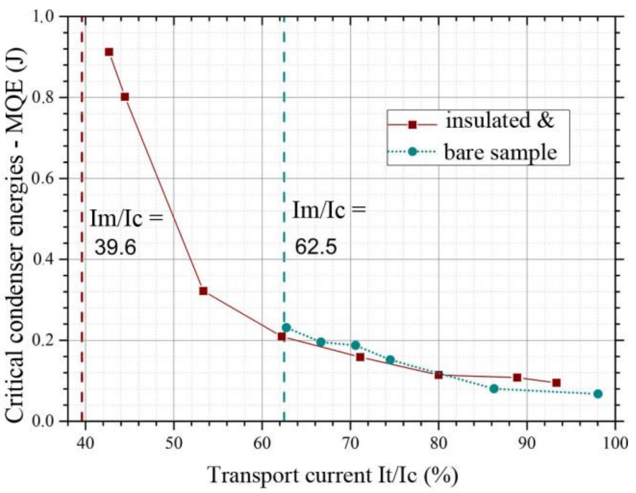

Fig. 6. MQEs for the directly cooled and thermally insulated YBCO tapes at different transport currents.

The process of normal zone initiation is illustrated in Fig. 5 for the thermally insulated YBCO tape at 45 - 48 A in the form of temporary dependencies of the voltage drop across the sample triggered by local heat pulses of increasing power.

Fig. 6 represents the critical condenser energies (considered us as MQEs) for both samples at different transport currents. The dashed lines show I_m/I_c ratios limiting the regions where any artificially created normal zone always collapses. In other words, these threshold values determine the region of currents where the stationary stability criterion of an HTS device is fulfilled.

Interestingly, the MQE values appeared to be almost the same for the thermally insulated and directly cooled samples within the 5 % experimental error. At the same time, the stationary stability limits vary greatly for different cooling conditions: I_m/I_c = 62.5 % for the bare sample and I_m/I_c = 39.6 % for the thermally insulated one.

4.3. Minimum lengths of the normal zone propagation.

Using the threshold U & I values taken from Fig. 5 the minimum NZP length (L_{NZP}) can be evaluated as $L_{NZP} = S_n \cdot U/(I \cdot \rho_n)$, where S_n and ρ_n are the cross-section and resistivity of the YBCO tape in the normal state correspondingly. Fig. 7 shows the dependencies of the L_{NZP} vs. transport current for both samples. It can be seen, that the values of L_{NZP} for the bare sample are lower than for the thermally insulated one. The possible reason is the higher temperature of the bare sample which is cased by the film boiling of LN2 onto its surface, whereas the presence of thermal insulation increased the thermal diffusion time constant for the insulated sample and, as the result, led to the nucleate boiling of LN2 with a higher heat transfer coefficient.

4.4. Normal zone propagation velocities.

NZP velocities were determined as the sample's voltage ramp rates measured at the different distances from the heater and divided by the factor of 2 to take into account the symmetrical propagation of the normal zone along the YBCO tape in the two directions.

It can be seen that the linear slope of the rising curve in Fig. 5 changes visibly as 8.6 s passed from the beginning of the heat pulse. In other words, two different NZP velocities V1 and V2 were registered for the sample operating at I_t/I_c = 0.42 in the conditions close to the adiabatic stability criterion.

The sharp increase of NZP velocity was apparently attributed to the changing of the heat transfer regime onto the surface of the heated sample. When free convection changes to nucleate boiling the heat transfer coefficient grows and, as the result, the temperature of the sample decreases. For instance, in [15] the same temperature decreasing process due to heat transfer regime changing was experimentally observed on Ni-W tapes.

Fig. 8 gives NZP velocities depending on transport current for both samples. It can be seen, that the existence of the two NZP velocities stops at transport currents $I_t/I_c > 0.9$. As NZP velocities for HTS tapes are two orders of magnitude lower than for LTS conductors there is a risk of a hot spot origination. The tape itself can be considered an internal resistive thermometer.

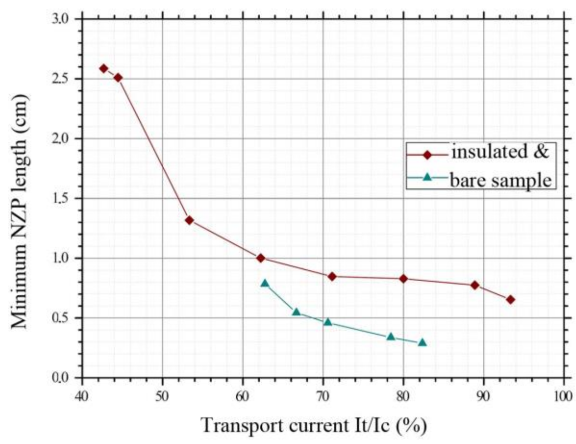

Fig. 7. Minimum NZP lengths vs. transport currents for the directly cooled and thermally insulated YBCO tapes.

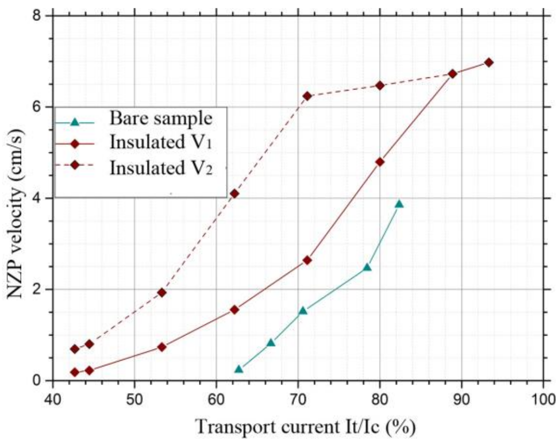

Fig. 8. NZP velocities vs. transport currents for the directly cooled and thermally insulated YBCO tapes (V1 and V2 correspond to two different NZP velocities registered for the thermally insulated sample).

Using the determined length of the normal zone together with the temperature dependency of the resistivity of copper from [1] the temperature of the YBCO tape within the normal zone can be evaluated. In this approach, the temperature is set to be uniform along the whole length of the normal zone due to the heat transfer to the coolant. The increasing of the voltage drop across the experimental samples caused by the normal zone expansion is shown in Fig. 9 together with the heat fluxes to the coolant (q) and heat transfer coefficients (h). The heat flux values were determined as the Joule heating power generated within the sample divided by the cooling surface. The heat transfer coefficients were estimated as the sum of thermal resistances [15] in the layer of thermal insulation and in the boundary layer between the sample surface and gaseous nitrogen surrounding the sample in the film boiling regime.

One second after the beginning of normal zone propagation, the heat flux to the coolant at $I_t/I_c = 0.62$ was equal to $2.24 \cdot 10^4$ W/m^2 and overheating 25 K. For example in works [8, 16], where the quench/recovery processes were investigated for a copper stabilized YBCO tape, film boiling changed to nucleate boiling at the threshold values of the heat flux $2.32 \cdot 10^4$ W/m^2 and overheating ΔT = 27 K. Basing on this comparison, we can conclude that in our experiments the heat transfer for the bare YBCO tape was developing at the film boiling of LN2 onto the sample's surface. Whereas in the thermally insulated sample there was a temperature gradient between the YBCO tape heated up to 152 K and the sample surface at 80 K (ΔT = 3 K) leading to the nucleate boiling of LN2 with a much higher heat transfer coefficient to the coolant.

The temperature ramp rate for the thermally insulated YBCO tape appeared to be 7 times higher than for the bare one reaching 75 K/s. In other words, it takes 3 s only to heat up to the room temperature for the sample operating in nearly adiabatic conditions.

4.5. Comparison to other superconductors.

Fig. 10. shows the comparison of MQE volumetric density vs. critical temperature margins $\Delta T_c(I,B)$ evaluated from the literature data for the HTS and LTS wires and tapes listed below:

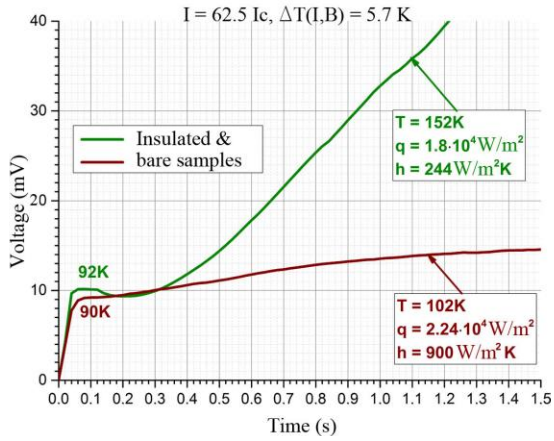

Fig. 9. The temporary dependencies of voltage drop across the directly cooled and thermally insulated YBCO tapes.

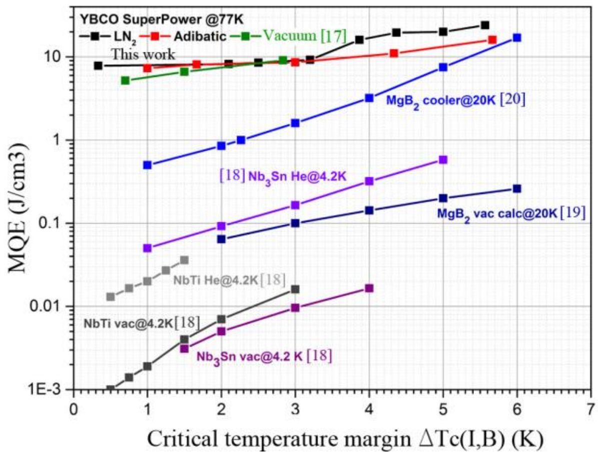

Fig. 10. The MQE volumetric density vs. critical temperature margin for HTS and LTS wires and tapes in different cooling conditions.

1. YBCO tapes (4 mm x 0.1 mm) at 77 K in self magnetic field either directly cooled with LN2 or in nearly-adiabatic conditions with I_t/I_c = 0.42-0.98 (this work);
2. Cryocooled (4 mm x 0.1 mm) YBCO tapes at 77 K in self magnetic field in vacuum with I_t/I_c = 0.8-0.95 from [17];
3. Multi-filamentary NbTi and Nb_3Sn wires 1 mm dia in a copper matrix placed in the external magnetic field B = 5.5 T either in vacuum or in liquid helium at 4.2 K [18];
4. Multi-filamentary MgB_2 wires at 20 K (3 mm x 0.65 mm) a nickel matrix placed either in vacuum [19] or cryocooled in the external magnetic field B = 1 T [20].

Using the critical temperature margin as a universal scaling parameter allowed us to compare the stability experimental results for different superconductors despite the varying samples' structures, test setups, thermal disturbance time constants, operational temperatures, transport currents, and background magnetic fields. The average stability growth appeared to be equal to 10 for NbTi, 20 for Nb_3Sn, 40 for MgB_2, and only 1.5 for the YBCO tapes at 77 K. Moreover, at low temperature margins the MQEs for the YBCO tapes at 77 K with direct LN2 cooling, in vacuum, and in nearly adiabatic conditions almost coincided.

5. CONCLUSION

In this work we have measured the stability characteristics of the copper stabilized YBCO tapes either on the bare sample directly cooled with LN2 or on the same tape covered by the 0.6 mm of Kapton insulation operating in nearly-adiabatic conditions. Minimum NZP currents, lengths, and velocities, as well as the minimum quench energies were determined at I_t/I_c = (0.42-0.98) and 77 K for both samples.

The MQEs appeared to be almost the same for the directly cooled and thermally insulated YBCO tapes. We explain this fact by the different heat transfer regimes to the coolant onto the surface of the samples. The bare sample was cooled through the film of nitrogen vapor whereas the other sample was covered with the Kapton insulation. Both samples, as the result, operated in nearly-adiabatic conditions during the normal zone propagation process. The difference is the considerably wider stationary stability region of transport currents for the bare YBCO tape. Any normal zone once artificially created always collapsed at transport currents I/I_c <0.62 for the bare YBCO tape, whereas the thermally insulated YBCO tape was thermally stable at transport currents I/I_c <0.40.

In the comparative experiments on normal zone propagation, the temperature rising ramp rates were also estimated. It was shown that, for instance, for the thermally insulated sample the temperature ramp rate was equal to 75 K/s in comparison to 10 K/s for the bare YBCO tape.

Furthermore, the existence of the two different normal zone propagation velocities in the thermally insulated tape was registered experimentally. The obtained information can be useful for HTS devices design.

ACKNOWLEDGMENT

The work was supported by the Russian Foundation for Basic Research through the grant 17-29-10005 ofi-m AAAA-A18-118122490093-8, agreement number 17-29-10005\20. The authors are grateful to Dr. Vladimir I. Shcherbakov for his help during the experiments. We also warmly thank Dr. Dmitry N. Diev for the proofreading of the manuscript.

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