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CURRENT REDISTRIBUTION AROUND THE SUPERCONDUCTING-TO-NORMAL TRANSITION IN SUPERCONDUCTING NB-TI RUTHERFORD CABLES

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Sufficient thermal-electromagnetic stability against external heat sources is an essential design criterion for superconducting Rutherford cables, especially if operated close to the critical current. Due to the complex phenomena contributing to stability such as helium cooling, inter-strand current and heat transfer, its level is difficult to quantify. In order to improve our understanding, many stability tests were performed on different cable samples, each incorporating several point-like heaters. The current redistribution around the heat front is measured after inducing a local normal zone in one strand of the cable. By using voltage taps, expansion of the normal zone is monitored in the initially quenched strand as well as in adjacent strands. An array of Hall probes positioned at the cable edge is used to scan the selffield generated by the cable by which it becomes possible to estimate the inter-strand current transfer. In this paper it is demonstrated that two different stability regimes can be distinguished depending on the local conditions for local normal zone recovery through heat and current transfer to adjacent strands. It is shown that in the first regime every normal zone will lead to a quench, while in the second regime a normal zone in one strand can recover. Combining the predictions developed using a novel version of the numerical network model CUDI and new measurement results, it is possible to derive characteristic quench decision times as well to calculate and predict the influence of a change in cable parameters.

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Current redistribution around the superconducting-to-normal transition in superconducting Nb-Ti Rutherford cables

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Abstract. Sufficient thermal-electromagnetic stability against external heat sources is an essential design criterion for superconducting Rutherford cables, especially if operated close to the critical current. Due to the complex phenomena contributing to stability such as helium cooling, inter-strand current and heat transfer, its level is difficult to quantify. In order to improve our understanding, many stability tests were performed on different cable samples, each incorporating several point-like heaters. The current redistribution around the heat front is measured after inducing a local normal zone in one strand of the cable. By using voltage taps, expansion of the normal zone is monitored in the initially quenched strand as well as in adjacent strands. An array of Hall probes positioned at the cable edge is used to scan the self-field generated by the cable by which it becomes possible to estimate the inter-strand current transfer. In this paper it is demonstrated that two different stability regimes can be distinguished depending on the local conditions for local normal zone recovery through heat and current transfer to adjacent strands. It is shown that in the first regime every normal zone will lead to a quench, while in the second regime a normal zone in one strand can recover. Combining the predictions developed using a novel version of the numerical network model CUDI and new measurement results, it is possible to derive characteristic quench decision times as well to calculate and predict the influence of a change in cable parameters.

1. Introduction

An important issue in the design of superconducting accelerator magnets is the level of thermal-electromagnetic stability against external heat sources. Due to friction as result of strand or cable movements or local beam losses, a short local heat deposition increasing the superconductor temperature is likely to occur. In recent measurements we have introduced voltage taps put locally on strand sections in the cable which allows investigating the stability mechanisms of the superconducting Rutherford type cable in much more detail.

Usually stability measurements on superconducting cables are performed with global voltage taps [1]. With such taps global quench propagation speed can be determined. Measurements of local current distribution by using voltage traces of a normal zone reported so far, were limited to single strands [2,3], a Rutherford cable with a steady state local heating [4] and a three-strand cable [5]. In the new measurements presented here, however, the very local propagation of normal zones through neighboring strands is made visible.

Graphite paste heaters that are positioned locally on a strand are used to introduce normal zones in small sections of a strand, see figure 1. Because the heaters are in direct contact with the strands in the cable they are at the same time used as voltage taps. The voltage development in multiple strand sections in a Rutherford type superconducting cables is traced by these voltage taps. Figure 2 shows the measured voltage traces across three adjacent strands (they all produce the same curve and will appear as one line) and the global voltage across a 60 cm long section of the cable. The average temperature of the strand section between voltage taps is calculated and has increased to 50 K after 70 ms. The visible decrease in cable current is a consequence of the limited power supply capacity to keep the current constant. The measurement shown is on a partially soldered LHC type II Nb-Ti cable with 36 strands tested at 12 kA, a magnetic field of 6 T and cooled by liquid helium. A quench propagation velocity of 40 m/s is deduced.

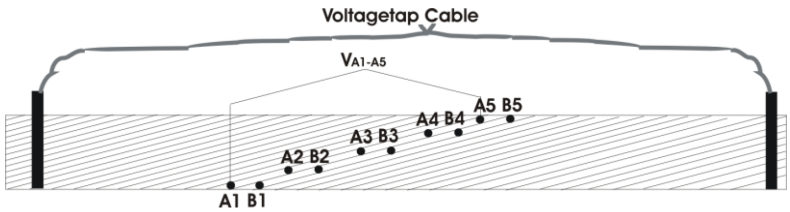


Figure 1. Schematic of the positioning of the global voltage taps on the cable sample with a length of 60 cm. The local voltage taps are combinations of two heaters that are positioned on the same strand. $V_{A1\text{-}A5}$ is an example of a voltage tap between points 1 and 5 on strand A (section length ~ 5 cm).

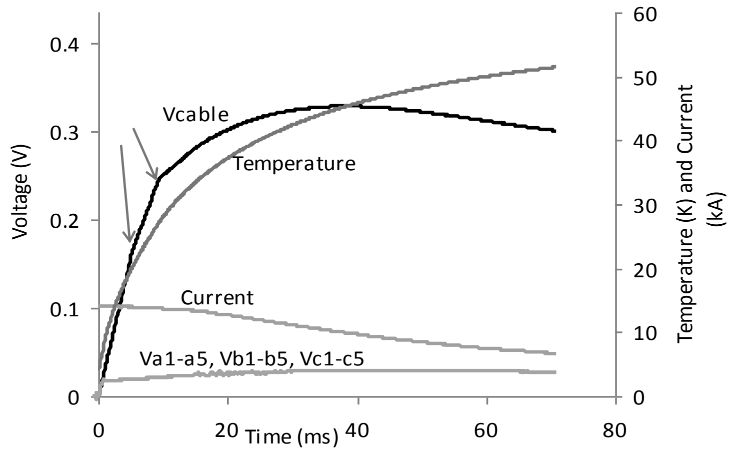


Figure 2. Measured characteristic voltage traces during the first 70 ms after the start of the normal zone. The arrows indicate the point where the normal zone passes voltage tap positions.

Here the focus is on the first milliseconds of the existence of the normal zone after the heat pulse was introduced on the strand. By comparing the measurements with the outcome of the CUDI [6] network model simulations, in great detail the local currents, voltages, temperatures and normal zone lengths around the superconducting to normal transition can be determined. The measurement setup is described in section 2 as well as the used samples. In section 3 the measurement results for two cables are presented and a qualitative comparison to a simulation result with CUDI is analyzed in section 4.

2. Experimental setup

The stability measurements are performed in the CERN cable test facility FRESCA. Cable samples of 2.4 m overall length are positioned in an external magnetic field, uniform along about 1 m, which is applied parallel to the broad face of the cable. On the broad face a 50 µm thick adhesive Kapton tape is placed with pre-fabricated holes of 0.5 mm diameter. The holes are positioned above single strands and filled with a small amount of graphite epoxy paste (Eccobond 60L). More details can be found in [7], [8]. During the curing of the epoxy, pressure is applied in such a way that a final resistance between 1 and 2 Ω is reached. Local heat pulses with a duration of 100 μs are introduced in the strand to determine the QE of the cable.

Measurements were performed on 8 different cable samples. They comprise the 28-strand un-cored LHC type I Nb-Ti cable and the 36-strand cored LHC type II Nb-Ti cable. They received different heat and soldering treatments. All experiments are cooled either by liquid helium at 4.3 K or cooled by superfluid helium at 1.9 K. The maximum applied external field is 9 T. In this paper we limit ourselves to two samples, of which the main cable sample properties are listed in table 1.

Table 1. Main specifications of the used samples.

	Sample 1	Sample 2
Type	Cored LHC type II	Cored LHC type II
Number of strands	36	36
Strand diameter (mm)	0.825	0.825
Transposition pitch (mm)	100	100
RRR	245	272
R_a (μΩ)	600-700	8000-9000
I_c (kA) at 4.3 K, 6T	14.7	14.1
Cable treatment	4 h in N_2 gas at 200 ºC + 10 h in air at 200 ºC	18 h in vacuum at 215 ºC + 58 h in air at 210 ºC

3. Measurement results

3.1. Different stability regimes

Normally the stability of a superconducting cable is described by a QE versus I/I_c curve. So these measurements and by using the local voltage taps also the energy needed to form locally a normal zone, the Enthalpy Limit (EL), is deduced, see figure 3. In the curve with the QE limit a kink is clearly visible, separating on the right the high I/I_c regime exhibiting single strand behavior and on the left the low I/I_c regime where current redistribution gradually becomes important thereby enhancing stability.. The high I/I_c part is defined as Regime I and the low I/I_c part as Regime II. The two regimes show very different behaviour to changes in interstrand heat conductivity, helium cooling, and interstrand contact resistance [9]. In the area between the EL and the QE curve a normal zone that recovered is observed. In some cases at $I/I_c < 0.5$ the recovery of normal zones in more than one strand is observed.

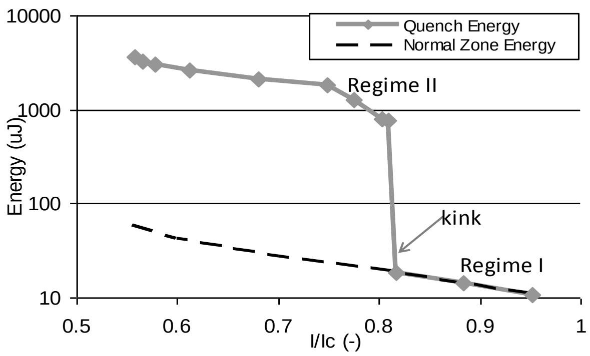


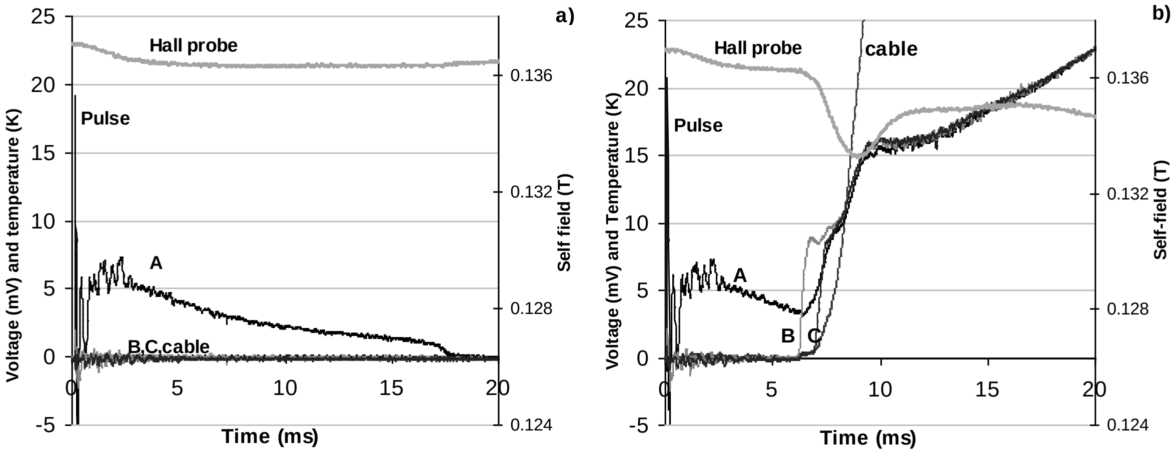
Figure 3. Typical Quench Energy and the Enthalpy Limit as function of I/I_c. In this case measurements for a cored and heat-treated LHC type II cable at 4.3 K and 6 T are shown.

3.2. Voltage traces during quench and recovery

By firing a pulse in heater A3 on sample 1 with an energy just below QE a local normal zone is created in only one strand. Figure 4a clearly shows the voltage for section A1-A5 gaining a maximum voltage of 6 mV. A sample current of 17.75 kA, an applied external field of 3 T and a temperature of

4.3 K with liquid helium cooling are used. The voltages of the neighbouring strands B and C remain zero. In this case the normal zone lasts for more than 17 ms. The Hall probe closest to strand A shows a decrease of 0.55 % in the measured self field. In the case the current of a normal conducting strand section is transferred to its two neighboring strands, a decrease of 1.9 % is calculated. Therefore it is assumed that 29% of the strand current is redistributed to its neighbors.

In figure 4b a slightly bigger heat pulse is given to the sample with an energy pulse just higher than QE. Until 6 ms the same behavior is visible in voltage trace A. At the 6 ms mark, the voltage in strand B is increasing rapidly with a quench propagation velocity that is higher than the global quench propagation velocity. This can be explained since the local I/I_c in strands B and C are much higher than the global I/I_c due to the increased current provoked by the normal zone in strand A and the increased temperature due to the contact with the hot spot in strand A. The most inhomogeneous current distribution is reached at 8 ms, where the hall probe signal is lowest.



Figures 4a and 4b. In figure a the heat pulse just below QE leads to a normal zone in strand A that recovers and in figure b a pulse just above QE provokes a quench. The voltages from strands A, B and C and the global cable are measured. The self-field is measured with one of the Hall probes.

3.3. Normal zone propagation in the transverse direction

By using voltage taps on five neighboring strands A1-A5, B1-B5, C1-C5, D1-D5, and E1-E5, the voltages in strand A to E are measured, showing the propagation of the normal zone. In figure 5 the voltage traces are shown after inducing a pulse in heater A3 in sample 2.

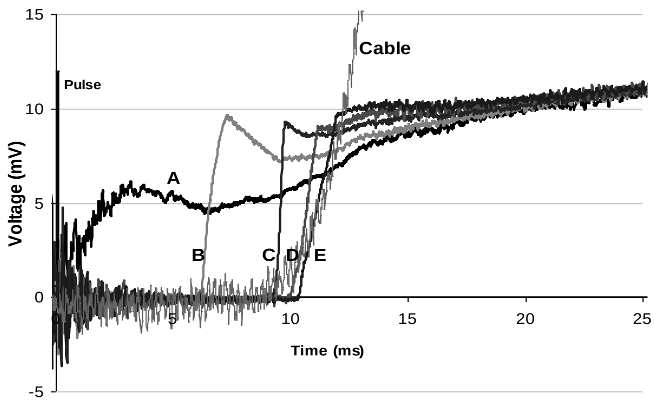


Figure 5. Strand voltage traces after inducing a pulse in strand A. The normal zone propagation in transverse direction towards strand B, C, D and E is shown with the global cable voltage.

The first 6.3 ms only a normal zone in strand A is present. At that moment a normal zone starts to grow rapidly in strand B with an initial velocity of 36 m/s to a full normal zone between the voltage taps at 7.5 ms. The normal zone propagation velocity in strand C is 72 m/s, in strand D 12.4 m/s and in strand E 13.5 m/s. The global cable voltage tap shows a quench propagation velocity of 12.5 m/s. Due to current redistribution the voltage in strand B decreases again until also strand C makes a transition to normal. At the 20 ms mark all voltage taps show the same voltage, indicating that all strands are in a fully normal state and the current is distributed homogeneously again.

3.4. Analysis of voltage trace signals

The voltage traces in figure 5 can be analyzed by making assumptions about the normal zone lengths in the strand sections and be used to reconstruct the current curve over time in each strand. A first important assumption is that the voltage traces only show the resistive current in the cable. This is supported by simulations with CUDI that have shown that current redistribution in this case takes place over a length of more than 1 meter and by the measured voltages on strand B, C, D and E that remain 0 V before the 6 ms mark.

A homogenous current distribution is assumed at the 0 and 25 ms mark. To fit the curve properly a non-linear growth of the normal zone in strand A is used, because of the decreasing current in this strand, to a full normal zone after 5 ms to fit the curve. The normal zones in strand B, C, D and E are assumed to grow linearly, as they show a high normal zone propagation speed in between 13 and 72 m/s, see figure 6a. The inductance of strand A is used as a free parameter to fit the voltage trace of strand A the first 6 ms. It is assumed that the current sharing from a strand with a normal zone is limited to its two neighboring strand. Figure 6b shows the obtained curve for the current distribution.

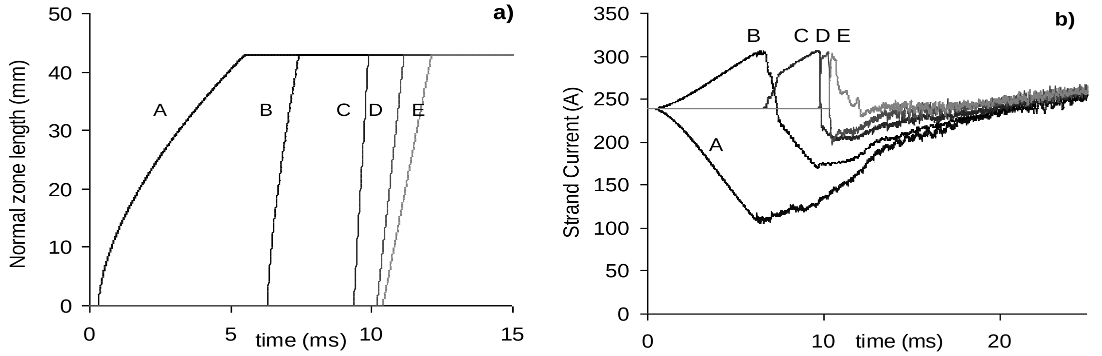
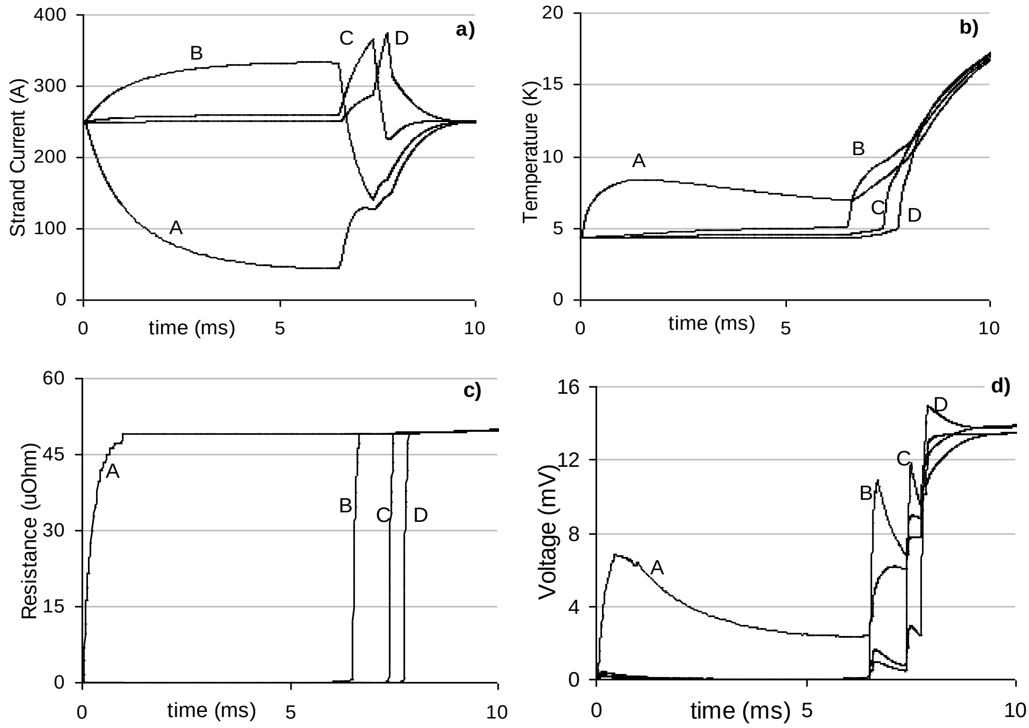


Figure 6a and b. In figure a the estimated normal zone length between the voltage taps 1-5 for strand A to E is shown and in figure b the deduced current in strands A to E.

4. Simulation results

With the network model CUDI calculations are performed to quantify the qualitative behavior of the cable during the superconducting to normal transition. In order to quantify the comparison between the simulation and the measurement the same strand design parameters and other parameters like bath temperature, cable current, applied field, RRR and R_a value are taken from the measurement of cable sample 2. The interstrand heat flow and helium cooling parameters are those estimated in [8]. To reduce calculation time we simulated an 8 strand cable model of 2.2 m long. For the high-R_a of 8.5 mΩ as in this sample, almost all current sharing takes place between direct neighbors and over a length of more than 1 meter. For cables with lower R_a more neighboring strands are involved, but the current redistribution takes place over a shorter section. As in the measurement a heat pulse is induced in strand A at t = 0 ms and from that moment the events in this strand and the neighboring strands B, C, and D are followed over a length of 47 mm. In figures 7a to 7d the average strand current, the average temperature, the normal zone length in this strand section and the voltage traces (includes resistive and inductive voltage) are displayed.



Figures 7a to 7d. a) The average strand current, b) the average temperature, c) resistance and d) the voltage traces of the 47 mm strand sections for strand A to D.

5. Conclusions

The longest time that a normal zone existed in our measurements, without quenching the cable was 17 ms. This happened at an I/I_c just below the I/I_c at the kink. This length tends to get longer for a lower R_a, but is also influenced by other parameters like interstrand heat conductivity.

Measurements with both voltage taps and hall probes have shown that 25 ms after inducing a local normal zone the current distribution is fully homogeneous again.

Simulation with an 8 strand model in CUDI has reproduced the characteristic measured phenomena fairly well. Much can be further improved by simulating the phenomena in a more precise way.

Both measurements and simulations show that a short local heat pulse can cause a normal zone in a strand that either can recover or lead to a cable quench.

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