Stability of Nb-Ti Rutherford Cables Exhibiting Different Contact Resistances

G. P. Willering, A. P. Verweij, J. Kaugerts, and H. H. J. ten Kate

Abstract—Dipole magnets for the so-called SIS-300 heavy-ion synchrotron at GSI are designed to generate 6 T with a field sweep rate of 1 T/s. It is foreseen to wind the magnets with a 36 strands Nb-Ti Rutherford cable. An important issue in the cable design is sufficiently low AC loss and stability as well. In order to keep the AC loss at low level, the contact resistance between crossing strands R_c is kept high by putting a stainless steel core in the cable. The contact resistance between adjacent strands R_a is controlled by oxidation of the Sn-Ag coating of the strands, like in the LHC. In order to investigate the effect of R_a on the stability of the cable, we prepared four samples with different R_a by varying the heat treatment and applying a soldering technique, resulting in values between $1 \mu\Omega$ to $9 \text{ m}\Omega$. The stability of each sample against transient point-like heat pulses was measured. The results of the stability experiments and a comparison with calculations using the network model CUDI are presented. It is concluded that variation of R_a has a strong influence on cable stability and that optimization of R_a is mandatory to properly design the cable for the SIS-300 magnets, or likewise for similar magnets that might be used at CERN for a possible LHC injector upgrade.

Index Terms—Magnets, minimum quench energy, stability, superconducting cables.

I. INTRODUCTION

THE stability of a superconducting cable against local disturbances is in general described by a curve presenting the Quench Energy QE as a function of the normalized current I/I_c as shown in Fig. 1 [1], where I_c is the critical current. Normally this curve exhibits a sharp ‘kink’ separating two distinctive stability regimes. The current at which the kink occurs is called I_{kink} . Regime I is the high I/I_c regime, where cable stability behavior is similar to the behavior of a single strand. Regime II is the low I/I_c regime, where current redistribution increases stability.

In order to produce cables that are stable at operating point against short point like disturbances it is preferable to stay in stability regime II, where stability increases by more than one order of magnitude. In measurement and simulation we will demonstrate how heat treatment or partial soldering can considerably influence cable stability in this regime.

This study was performed to be able to choose the correct inter-strand contact of the cables for the FAIR SIS 300 high ramp rate magnets [2]. GSI prepared cored Rutherford cables

Fig. 1. Quench Energy versus I/I_c curve with characteristic points and area's, showing regime I on the right side of the kink and regime II on the left side.

with four different surface preparations in order to vary the contact resistance between adjacent strands (R_a) as much as possible. Note that GSI requires a high R_a -value in order to keep the AC loss at a reasonable level. The stability of the four samples is measured at CERN in the cable test facility FRESCA [3]. Simulations are performed with the network model CUDI [4], and comparison to the experimental curves, gave us a profound insight in the mechanisms of cable stability and the effect of the strand surface treatment on the stability.

In Table I the main design parameters of the tested strand and cable are listed. The cable is very similar to the outer layer cable of the LHC dipole magnets at CERN, with the exception of a smaller filament diameter, a smaller filament twist, and the presence of a core. Four identical cable pieces were given different treatments. The four samples are denoted “low- R_a ”, “medium- R_a ”, “high- R_a ”, and “ultrahigh- R_a ” and some additional measured characteristics are shown in Table II. R_a is measured according to [5]. These surface treatments did not only change the R_a -value, but at the same time also the inter-strand heat conductivity k_{is} , the RRR value, and may possibly affect the heat transfer between the strand surface and the helium (k_{He}). Note that when these cables would be used in a magnet, the final curing of the coil would again change the values of these parameters.

II. FACTORS INFLUENCING CABLE STABILITY

Based on our experiments and modeling, the criteria for developing a quench or recovery in a cable can be described according to Table III [6].

In regime I the stability behavior is similar to that of a single strand. In this regime current redistribution does not affect the quench level and the value of R_a does therefore play no role. The most significant parametric effect on stability is caused by a change in k_{He} , followed by k_{is} and the RRR-value.

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G. P. Willering and H. H. J. ten Kate are with the CERN, Geneva, Switzerland, and also with the University of Twente, Enschede, The Netherlands (e-mail: gerard.willering@cern.ch).

A. P. Verweij is with CERN, Geneva, Switzerland.

J. Kaugerts is with GSI, Darmstadt, Germany.

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TABLE I
DESIGN PARAMETERS OF STRAND AND CABLE

<i>Strand</i>	
Strand diameter	0.825 mm
Filament diameter	6.0 μ m
Filament twist pitch	15 mm
Cu/Nb-Ti ratio	1.95
Strand coating	Sn-Ag (Staybrite)
Critical current density J_c	2700 A/mm ² (5 T, 4.2 K)
Critical current density J_c	2130 A/mm ² (6 T, 4.2 K)
<i>Rutherford Cable</i>	
Strand number	36
Transposition pitch	100 mm
Width	15.1 mm
Thickness, thin edge	1.362 mm
Thickness, thick edge	1.598 mm
Mid-thickness	1.480 mm
Core size and material	13 mm wide, 25 μ m thick, Stainless steel 304
Crossover resistance R_c	20 m Ω

TABLE II
MEASURED CABLE PARAMETERS

Identification	Treatment	RRR	R_a ($\mu\Omega$)	I_c (A) 6 T, 4.3 K
low- R_a	partially soldered at 200 °C + 3 minutes at 250 °C	346	< 1	14689
medium- R_a	no treatment	89	60 – 70	14240
high- R_a	heat treatment	245	600 – 700	14741
ultrahigh- R_a	18h at 215 °C in vacuum + 58h at 210 °C in air	272	8000 – 9000	14112

TABLE III
QUENCH CRITERIA FOR THE TWO MAIN STABILITY REGIMES

	No Quench	No normal zone occurs in the heated strand.
Regime I	Quench	Normal zone occurs in the heated strand, no recovery possible.
	No Quench	A normal zone in the heated strand leads to current redistribution, but the other strands stay superconductive. Recovery takes place.
Regime II	Quench	Normal zone occurs in the heated strand, causing current redistribution leading to a normal zone in the adjacent strand. No recovery possible.

In regime II, however, the stability is also influenced by R_a , because current redistribution takes place as soon as a normal zone is created in one strand. In order to improve the stability a shift of the kink to higher I/I_c and an increase of the quench level left from the kink are highly desirable. This can be achieved by increasing k_{He} and the Residual Resistance Ratio of the copper RRR, and decreasing k_{is} and R_a . Note that measurements and simulations show that current redistribution mainly occurs through the adjacent contacts and not through the crossing contacts. This is certainly true for $R_c \gg R_a$, but it even holds when these parameters have the same order of magnitude.

III. EXPERIMENTAL SETUP

The stability measurements were performed in the CERN cable test facility FRESKA. For these tests we use cable samples of 2.4 m length of which 1 m was positioned in the external magnetic field which was applied parallel to the broad face of the cable. On the broad face a 50 μ m thick adhesive Kapton

Fig. 2. Mounting of the graphite paste heater on a strand surface.

tape was placed with pre-fabricated holes of 0.5 mm diameter. These holes are positioned above single strands and covered with a small amount of graphite epoxy paste (Eccobond 60 L). A copper strip of 1 mm wide was placed over the paste and held in place by adhesive Kapton tape. More details can be found in [7]. During the curing of the epoxy, pressure was applied in such a way that a final resistance between 1 and 2 Ω is reached. A similar set-up of heaters was used by [8]–[10].

In Fig. 2 the mounting of the heaters is shown schematically. Usually three heaters per strand are positioned on the surface of about 5 consecutive strands. In this way the heaters can act as voltage taps as well, by measuring the voltages across single strands. Here we limit ourselves to the stability behavior of the central heaters.

Heat is deposited in the strand by applying a square electrical pulse with a duration of 100 μ s and powers up to 40 W. The superconducting strand is used as a return current lead. Only the heat entering the strand before the quench decision moment (QDM) takes place has to be taken into account. Although the heaters are in direct contact with the strand, the heat pulse will enter the strand with a delay. Modeling is performed [11] showing the exact shape of the heat pulse entering the strand. By integrating the heat from the start of the pulse to the QDM, one obtains the effective heat that has to be taken into account. The scaling factor F_{sc} is defined as the ratio between the effective quench energy (QE) and the input pulse energy (E_{inp}). As justified in [11] we will apply $F_{sc} = 0.4$ in regime I (having a QDM of about 100 μ s) and $F_{sc} = 0.9$ in regime II (having a QDM of about 0.5 ms).

IV. MEASUREMENT RESULTS

The QE measurement is performed by ramping the current to the desired level with constant temperature and field. A heat pulse is deposited onto one strand of the cable. If no quench follows, the cable is quenched manually to prevent non-uniform current distribution due to the creation of local normal zones. Consecutive pulses are applied to determine the quench energy within 5 % accuracy. The scaling factor F_{sc} is applied in order to obtain the effective quench energy QE. Such experiments are performed for several heaters per sample and at different temperatures and fields. For clarity, here only data obtained at 4.3 K and 6 T are presented.

Fig. 3 shows the obtained QE from the stability measurements for the four cable samples. The position of the kink varies quite dramatically from $I/I_c \approx 0.62$ for the highest R_a to $I/I_c > 1$ for the lowest R_a of the cable. It is clearly visible that for three curves Regime I is not significantly affected by the change of parameters. This is expected, because in as regime k_{is} plays a minor role to cool the strand as compared to the helium cooling. The R_a -value itself is also unimportant because current redistribution as a stabilizing feature does not occur. For the low- R_a sample current redistribution always takes place in

Fig. 3. Quench energy plotted against I/I_c for the four differently prepared cable samples at a temperature of 4.3 K and an applied field of 6 T. The dashed line shows the calculated QE for a comparable single strand with a $100 \mu s$ square pulse.

TABLE IV
CONTACT SURFACES AND HELIUM VOLUME

Contact surface between strand and Helium $A_{He} (mm^2)$	643
Contact surface between adjacent strands $A_a (mm^2)$	144
Helium volume per strand $V_{He} (mm^3)$	12.3

multiple strands and stability regimes cannot be defined. The quench level left of the kink tend to increase if the kink moves to lower I/I_c values. This can be attributed to the lower thermal interstrand conductivity.

V. SIMULATION RESULTS

Simulations were performed with the network model CUDI to better understand the measurements. In CUDI, the cable is discretized in small strand sections and all currents and temperatures are solved as functions of time. The main equation that needs to be solved in the thermal module for every small time step dt is:

$$c_p \frac{\Delta T_s}{dt} V_s = P_{inp} + I_s^2 R_s + I_a^2 R_a - k_{He}(T_s - T_{He}) A_{He} - k_{is}(T_s - T_a) A_a - k_s \frac{dT_s}{dx} A_s \quad (1)$$

With c_p specific heat, T_s temperature, V_s volume, I_s the current, R_s resistance, k_s thermal conductivity and A_s the cross-section of a given strand section. P_{inp} is the power from the external pulse, I_a the current through the adjacent contacts, T_{He} the helium temperature, T_a the temperature of the adjacent strand, A_a the contact surface between adjacent strands and dx the spatial step size in longitudinal direction.

For this model we need an accurate description of strand and cable parameters, as described in Tables I and II. In [12] the topology of the LHC type II cable is described in detail, revealing the surfaces and volumes of the strands and helium. For our cable we assume that due to the creep of the kapton tape no helium exists on the outer surface of the cable, but only on the inner surface. The keystone angle is ignored and the surfaces, volumes and contact resistances are kept constant across the cable width. Table IV shows the given parameters per meter strand averaged over the cable width as used in the simulations.

Heat transfer to Helium I consists of multiple regimes [13]. Simulations show that the most important regime is the transient cooling regime. When the accumulated heat transferred

Fig. 4. Quench Energy versus I/I_c showing the effect of varying R_a between 22 and 650 Ω , with $RRR = 89$.

Fig. 5. Quench Energy versus I/I_c showing the effect of varying RRR between 50 and 300, with $R_a = 65$.

into the helium exceeds a certain limit, the nucleate boiling regime starts. Because this limit is governed primarily by the physical properties of helium and to a much smaller extent by the strand surface conditions a value of $20 J/m^2$ [14] is assumed here. The unknown parameters available to fit the simulated to the measured curves are:

— Interstrand heat conductivity parameter $f_{is}[W/m^2/K^{n-int}]$ used in:

$$k_{is} = f_{is} \cdot T_{nis}^{n_{is}} \quad (2)$$

— Transient helium cooling parameter $\alpha_{trans}[W/m^2/K^{n-trans}]$ used in:

$$k_{He} = \alpha_{trans} \cdot (T_s^{n_{trans}} - T_{bath}^{n_{trans}}) \quad (3)$$

with $n_{is} = 2.25$ [15] and with $n_{trans} = 4$ [13].

Figs. 4 and 5 show results of simulations with varying R_a and RRR .

To better understand the influence of f_{is} and α_{trans} on the QE first simulations by varying these parameters independently as shown in the Figs. 6 and 7 are performed. Note that the effect of changing a combination of parameters can make the effects stronger or weaker. The main observation is that an increase in f_{is} decreases the quench level in Regime II and an increase in α_{trans} shifts the position of the kink to the right and increases the quench level in Regimes I and II.

The simulated curves that fit the measured curves best are shown in Fig. 8. Table V shows the parameters used for these best fits.

The expected decrease in f_{is} (and hence k_{is}) for increasing R_a is clear. From literature it is well known that the Kapitza conduc-

Fig. 6. Quench Energy versus I/I_c showing the effect of varying f_{is} between 10 and 100.

Fig. 7. Quench Energy versus I/I_c showing the effect of varying α_{trans} between 20 and 200.

Fig. 8. Measured (dashed curves with markers) and calculated (solid lines) Quench Energy versus I/I_c .

TABLE V
OBTAINED FITTING PARAMETERS

Identification	a_{trans} [W/m ² /K ⁿ]	f_{is} [W/m ² /K ⁿ]
low- R_a	50	1530
medium- R_a	140	50
high- R_a	77	30
ultrahigh- R_a	30	25

tance is highly dependent on the surface condition like oxidation and coating [16]. Both oxidation and solder coatings decrease the Kapitza conductance on which the transient conductance is based. This confirms the observed variation in a_{trans} . The untreated medium- R_a sample shows the highest value for a_{trans} .

Measurements by [17] on strands with the same coating show a comparable value for a_{trans} .

VI. CONCLUSIONS

By applying four different kinds of treatments to a cored Rutherford cable we have varied R_a , but at the same time also other parameters like RRR, k_{is} and k_{He} . Our stability measurements show that the Quench Energy versus I/I_c curves change drastically. The position of the so-called 'kink' in these curves is highly determining the cable stability and, as expected, the position of the kink is shifted to higher I/I_c with lower R_a . The quench level left from the kink becomes higher for higher R_a , mainly due to the decrease in f_{is} .

Depending on the I/I_c operating point our advice for the cable design for the SIS-300 magnets is to aim for the lowest possible R_a at which the AC loss is sufficiently low. The measurements show that an R_a of 650 $\mu\Omega$ still gives a kink at $I/I_c = 0.75$, a value which is sufficiently larger than the foreseen operating point of $I/I_c = 0.58$.

The results of the network model CUDI are in good agreement with the measurement results. The obtained fitting parameters are consistent with the expected parameter change due to the surface treatments of the samples.

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