CROSSOVER RESISTANCE OF SUPERCONDUCTING CABLE FOR FAST-RAMPING MAGNETS OF PARTICLE ACCELERATORS

I.V. Bogdanov, S.S. Kozub, P.A. Shcherbakov, L.S. Shirshov, P.I. Slabodchikov,
L.M. Tkachenko, V.V. Zubko, Institute for High Energy Physics, Protvino, Moscow region, 142281

Abstract

Fast-cycling magnetic fields, produced by superconducting magnets of modern accelerators, generate cable losses, which reduce with increase of contact resistance between wires in the cable. On the other hand the contact resistance has to have enough small value in order to provide flow of currents between wires. At IHEP it was carried out the study of crossover resistances in Rutherford type superconducting cable with a different resistive coating of wires in order to find the optimal coating, satisfying both above-mentioned conditions. Values of crossover resistance were measured for 19-strand cables, made from wires with NbTi filaments into copper matrix with a different coating (Ni, Cr and natural oxide). Also dependence of resistance on pressure was studied in the region, corresponding for pressure values, produced in the coils of superconducting magnets for accelerators. Besides the obtained experimental results, the description of features of samples and measuring technique are presented as well as the outcome of calculations of cable component of losses for fast-ramping dipole magnet with two-layer coil.

INTRODUCTION

Magnetic field ramp rates in superconducting magnets of present particle accelerators (Tevatron, HERA, RHIC, LHC) do not exceed 0.1 T/s, whereas developed machines intend to use the superconducting magnets with fields up to 5-6 T the ramp rate up to 1T/s (GSI) and even 1.5 T/s (CERN). For attainment of such high fields the Rutherford-type cable is used, which permit to achieve the maximum current density into the coil of magnets.

Into magnet coils the magnetic field change causes the heat releases, which are stipulated hysteresis losses in SC wires, eddy current losses into wire matrix and eddy current losses in cable. Cable component of AC losses varies in inverse proportion to the interstrand contact resistances, for example see equation in [1,2]. It is clear that AC losses can be effectively controlled by increasing the interstrand contact resistance by: adjusting the level of native oxidation of strand, or coating it, or by inserting a ribbon–like core into the cable itself. There is a lot of papers concerning the theme of modifying of inter strand contact resistance. But whatever approach is taken the resistance values show very wide spread, e.g. see [3]. This caused by the wide range of processing condition (pressure, temperature and time) to which the cable is exposed during the magnet manufacture. So the goal of the experiment described in this report was to measure the interstrand contact resistance namely for the same cable and magnet manufacture process that IHEP plan to use in the quadrupoles [4] for SIS300 accelerator ring of FAIR.

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EXPERIMENTAL METHOD

It is accepted to distinguish the resistance R_c – resistance of each crossover contact and R_a, which is the side-by-side resistance between adjacent pairs of strand. The method of measurement of interstrand contact resistance, which is widely used in the last time, is a so-called VI technique [5]. That allows to obtain values of R_c and R_a. Unfortunately, as it was verified in [6] VI method is strongly dependent upon sample length: the results show significant differences in interstrand resistances when the sample length is smaller than one cable transposition length L_p.

As long as the study of resistance under varying pressure was one of the main tasks of this research, but our test equipment has the 50 mm limitation on the sample length, therefore the measurements were conducted by the Morgan method [7] on the samples, length of which equals to one half of transposition length. The main drawback of application this method to our samples is the impossibility to obtain the value of R_a, but only R_c. Schematically sample is shown in fig. 1.

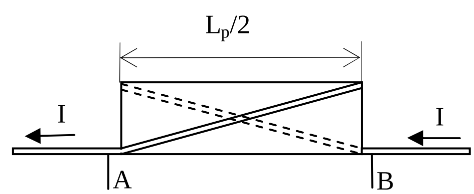

Figure 1: Sketch of samples for Rc measurement.

It is measured the resistance R_{AB} between the strands, which belong to different layer of cable and which cross into the center of sample. Than from the obtained resistance R_{AB} the value of crossover resistance R_c is determined with the help of simple ratio: $R_c = 1/2 \cdot N \cdot R_{AB}$, where N – the number of strand in cable. For our samples this approximate formula provides 5% accuracy. Traditional four-point technique was used for R_{AB} resistance measurements. The measurement was performed at the liquid helium bath (4.2K) with the help of high-sensitivity, low-noise acquisition system built on the base of Agilent 34420A nanovoltmeter and Agilent 34970A switch unit controlled via IEEE-488 instrumental bus. Current was brought from the 100 A power supply.

Slow current ramp was used during measurements. So the value R_{AB} was determined from the slope of voltage versus current characteristics.

All tested cables were made from the same original wire and differs from each other by the type of coating only, Table 1. Metallic coatings were applied by electrolytic techniques.

Table 1: Supercondicting NbTi cable.

Number of strands	19
Strand diameter, mm	0.85
Cable width, mm	8.5
Average thickness, mm	1.46
Transposition length, mm	62
Material of coating	Cr, Ni or natural oxide
Thickness of metallic coating	1μm

The stacks of insulated cable pieces were pressed into mould up to pressure of 70 MPa. After curing at the temperature regime shown in fig. 2 the testing samples with the length of 31 mm were cut in accord with fig. 1.

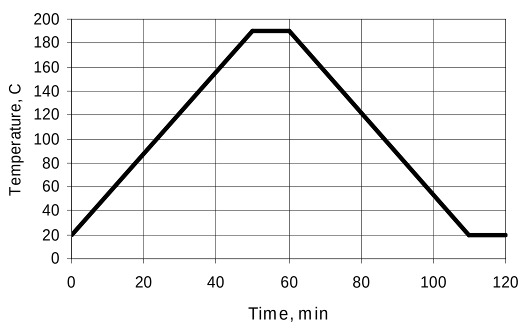

Figure 2: Temperature cycle for curing of samples.

Then samples were locked into sample holder of special device [8] assigned for creation of pressure on the sample surface. Maximum applied pressure was about 90MPa.

RESULTS OF MEASUREMENTS

Under the cyclic mechanical loading the resistance decrease consequently form cycle to cycle. Usually about ten cycles are required before the resistance becomes stable and its value becomes few times lower in comparison with the first loading cycle. As the example, in fig. 3 the dependence of crossover resistance close to maximum applied pressure versus cycle number is presented for three Ni coated samples. Such behaviour was true for any coating. One can see that at the measurements the adequate number of preparatory cycles should be made preliminarily. In cases when such training was not spent it is necessary to take this effect into account during the data analysis or loss estimation.

Figure 4 presents the dependences of crossover resistance R_c upon pressure on the cable surface. Loading and unloading branch of curves are presented for each sample. Numbers of samples are shown in figure.

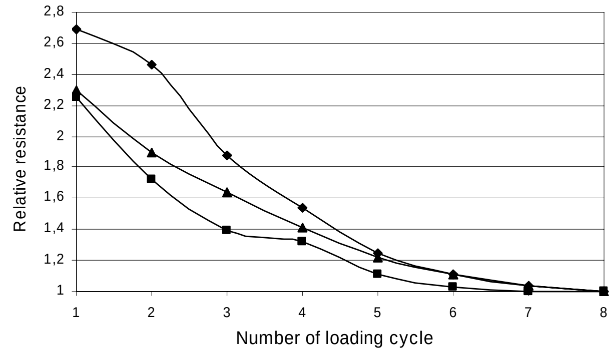

Figure 3: R_c evolution in Ni coated cable upon the loading cycle number (relative to eight cycle)

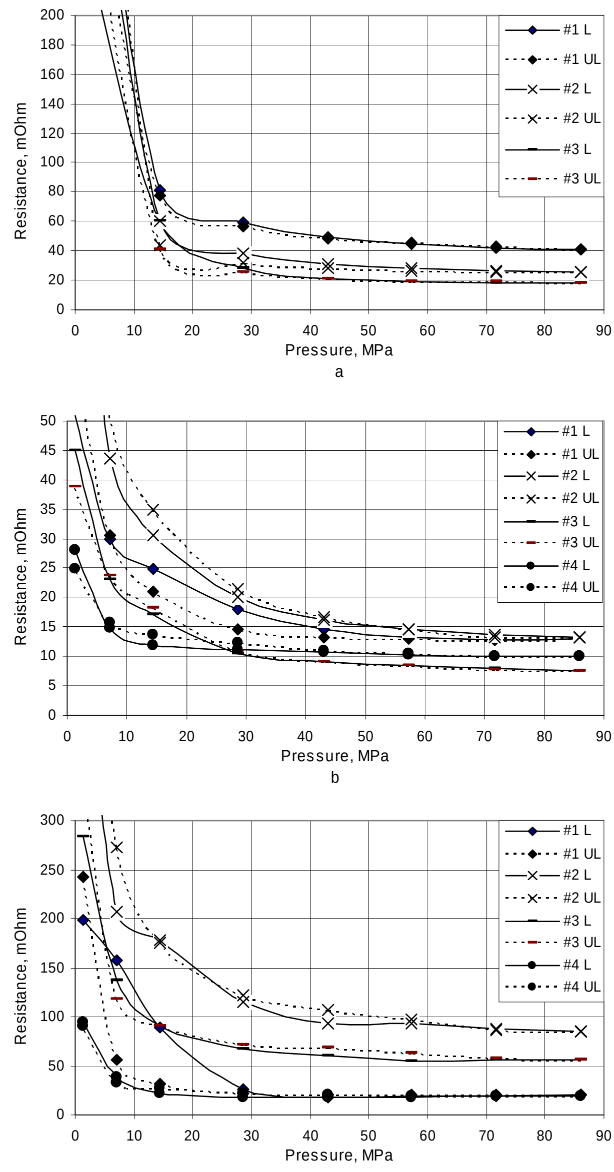

Figure 4: R_c versus pressure for the groups of samples with Cr (a), Ni (b) and natural oxide (c) layer on the strand surface. In legend: L –loading, UL – unloading.

From these pictures it is obvious that at the pressures greater than 30-40 MPa the Rc changes very little. Their values at the pressure ~80 MPa are summarized in table 2.

Table 2: R_c of cables with different resistive coatings at the pressure 80MPa, mOhm.

Sample No.	Chrome	Nickel	Natural oxide
1	41	13	20
2	26	13	84
3	18	8	54
4	-	10	19

For Ni-coated cable the spread of data is minimum, resistance values are tight, whereas the chrome-coated samples show two-time spread. Obtained values for cable with natural oxide are few time greater than previously tested samples made at longer curing time [3]. Also oxided sample show maximum (quadruple) spread, i.e. the natural oxidization process gives less-controlled result.

EXPECTED LOSSES IN MAGNETS

Let us take a look how such values of interstrand resistance may reflect on the losses in fast-cycling magnets. The cable components of AC losses were estimated for the dipole [9] and quadrupole [4] taking into account the spread of obtained data, table 3.

Table 3: Cable component of AC losses per one cycle for magnets with different coating of cable strands, J/m.

	Chrome	Nickel	Natural oxide
Dipole (spread of Rc)	1.3 - 2.9	4.0 – 6.4	0.6 – 2.7
Dipole (averaged Rc)	1.8	4.7	1.2
Quadrupole (spread of Rc)	0.02 - 0.04	0.06 - 0.1	0.01 - 0.04
Quadrupole (averaged Rc)	0.028	0.07	0.018

Losses were calculated for SIS300 cycle: for quadrupole - G_{min} = 10 T/m, G_{max} = 45 T/m, Δt = 3.5 sec and for dipole - B_{min} = 1.6 T, B_{max} = 6 T, Δt = 3.5 sec.

Due to the adjacent resistances Ra are unknown we supposed that R_a=R_c. As it is necessary to expect that R_a should be more than R_c [6], it gives top estimation of losses. However in considered magnets the losses in a cable are predominately governed by crossover resistance R_c, so such approach gives a slightly overestimated value of losses.

Presented cable losses for averaged R_c make only 2-8 % of the total losses in a dipole and are quite negligible (<0.3%) in quadrupole. Thus any considered coatings very effectively suppress a cable component of AC losses.

CONCLUSIONS

Interstrand resistance of cable with natural oxide or with Cr or Ni coating has a big enough value.

Any type of considered coating reduces the eddy current losses in cable to the reasonable level despite the spread of interstrand resistances. But natural oxide is less preferable due to the worst mechanical durability.

However, very large values of contact resistances could to make the worse the conditions of current redistribution between wires that can result in the decreasing of critical current in cable and its stability. This requires thorough R&D of cable stability including experimental check on model magnets.

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