Simulation of electromagnetic and thermal processes in Rutherford superconducting cables during the initiation of a quench

V Zubko\(^1\), I Bogdanov\(^1\), S Kozub\(^1\), P Shcherbakov\(^1\), L Shirshov\(^1\), P Slabodchikov\(^1\), L Tkachenko\(^1\)

\(^1\)Institute for High Energy Physics, Protvino, Russia, 142281

E-mail: Vasily.Zubko@ihep.ru

Abstract. Thermal stability for superconducting fast-cycling dipoles will play a vital role. The coupled numerical simulation of electromagnetic and thermal processes in Rutherford superconducting cables during the initiation of a quench was carried out. The network model has been combined with thermal analysis, which allows one to model quench dynamics, including the effects of current redistribution in strands, discontinuities and inhomogeneity, the initial heating in strand, and as results occasional quench recovery or runaway quench propagations.

1. Introduction

One of the main requirements to superconducting magnet is its stability. The stability of superconducting magnet can be estimated by means of a temperature margin (or an enthalpy margin) and a minimum quench energy (MQE). The main characteristic of superconducting magnet is AC losses in cables and strands, which have to be reduced in fast-cycling magnets. For reduction of cable losses, it needs to use either a cable with stainless steel core \([1, 2]\) or a cable with resistive coating strands. An experiment (in liquid helium at 4.3 K) to measure the effect of cable \(R_a\) on MQE of the cored cable was undertaken at CERN to determine, what the maximum value of \(R_a\) could be before cable stability is affected \([1]\). Here \(R_a\) is a resistance between adjacent strands. Strand coating, increasing contact resistance in a cable, can change MQE value. Study of MQE for cables with different strand resistive coatings has been made in IHEP. This article considers a correlation between contact resistance in a cable and MQE on the base of calculated and measured results.

Calculations of MQE in Rutherford cables are complex and require detailed non-linear multiphysics models. Last time large efforts have been devoted to an investigation of MQE multistrand superconducting cables. Researches in complex thermal-hydraulic and electromagnetic phenomena are presented in \([3, 4, 5]\). A code for the coupled numerical simulation of electromagnetic and thermal processes in Rutherford superconducting cables has been developed in IHEP. A computer code allows one to perform analysis of transient thermal and electrodynamics processes during the initiation of a quench in any type of Rutherford cable, which are subjects to global and/or local variations in field, transport current and external heat release.
2. Computational model

The computer code consists of electrodynamics and thermal parts.

The electrodynamics part of the code is based on a network model. The network model in detail is described in [6]. Cable of length \( L \), containing even number of strands \( N_s \), has a transposition length \( L_p \). The cable can be divided into \( N_s \) bands of length; each band can be decomposed into a collection of subnetworks. Within each subnetwork, the crossover and adjacent electric contacts between strands are represented by ohmic crossover \( R_c \) and adjacent \( R_a \) resistors; each section of strand is replaced by a piece of strand with a resistance and a self inductance; each strand section is linked to every other strand section in the cable by a mutual inductance.

The network model can be formulated in equations:

\[
\sum_{j=1}^{N_s} I_{s_i} R_{s_j} + \sum_{j=1}^{N_s} I_{s_j} R_{s_i} + \sum_{j=1}^{N_s} \partial U_{s_j} = \frac{dB}{dt},
\]

\[
\sum I_s + \sum I_c + \sum I_s = 0 \quad (1)
\]

Here \( t \) is time; \( I_s \) is a strand current; \( I_c \) is a current between adjacent strands; \( I_s \) is a current between crossing strands; \( B \) is a magnetic field. The voltage over a strand is

\[
\partial U_{s_j}(l,z)=V_n(I_{s_j}) + \sum_{i=1}^{N_s} M_j(t) \frac{dI_{s_i}}{dt}, \quad V_s(I_s) = U_s \left( \frac{I_{s_i}}{I_s(T,B)} \right)^n, \quad (2)
\]

\( z \) is a coordinate along strand; \( M_j \) is mutual inductance; \( I_s(T,B) \) is the critical current, when voltage \( U_s = 1 \mu V/cm; n = 30 \) for NbTi superconductor.

The thermal part can be formulated by the thermal equations for each component (strands, helium):

\[
(c_i \rho_s) \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial z} \left( \lambda_i \frac{\partial T_i}{\partial z} \right) - \sum_{j=1}^{N_s} \lambda_i (k_i T_i - T_j) - \sum_{j=1}^{N_s} (a_i(T_i) - T_j) + q_i(T_i, T, B) + q_{ic} + q_{mi}(z, \tau)
\]

\[
(\rho_s) \frac{\partial H}{\partial t} = \sum_{i=1}^{N_s} (a_i(T_i) - T_j) \quad (3)
\]

where \( c_i = c(T_i, B) \) is the specific heat capacity of a strand; \( \rho_s = \rho(T_i, B) \) is a specific density of a strand; \( \lambda_i = \lambda(T_i, B) \) is a thermal conductivity of a strand; \( S_i \) is a cross section of the strand; \( P_i \) is a perimeter of contact between neighbour strand; \( P_i \) is a function of coordinate; \( q_i(T_i, T, B) = I_{s_j} V_s(I_{s_j}) \) is the resistive heat in a strand; \( q_{ic} \) is a resistive heat in \( R_c \) and \( R_a \); \( q_{mi} \) is initial thermal disturbance; \( k \) is the heat transfer between contacting strands, \( k = (1/k_{cont} + (d/2)/\lambda(T_i) + (d/2)/\lambda(T_j))^{-1} \) with the strand diameter \( d \) and \( k_{cont} \) is a heat transfer of the contact between contacting strands, given by: \( k_{cont} = x T^b \), with typical values for \( x \) of 100 - 1000 W/m²/K\(^{(1-b)}\) and \( b = 1.5 - 2.5 \) [3]; \( U \) and \( H \) are temperature and enthalpy of helium; \( \Pi_i \) - the perimeter of contact between strand and helium; \( \alpha_i(T_i, U_j) \) is the heat transfer from strand to the helium. \( \alpha_i(T_i, U_j) \) is calculated in code by usual mechanism heat flow to helium I [7]. Heat transfer to the helium is defined by transient regime (Kapitza regime) [7], and 3 regimes for the steady-state heat transfer: natural convection, nucleate boiling and film boiling. Recommendations from [8] are applied in the code for modelling of transition between different regimes. A helium volume in an insulated cable consists of about 12% from volume of strands in the cable. The discretization of the cable for the thermal model is the same as for the electrodynamics model.

The computer code simultaneously solves the thermal and electrodynamics equations by the finite difference method (implicit difference scheme). Because of there is non-linear behaviour of the voltage over the strand section, the resistive heat in the strand, heat capacity, heat conductivity, heat flows between neighbour strands and heat flow to helium are used an iterative algorithm for each time step. Typically the required accuracies are \( 10^{-3} \) A for the currents and \( 10^{-4} \) K for the temperatures [3].

The internal parameters of the cable, such as contact resistances, critical current, cooling rates etc. can
be varied along the length and across the width. In this way, all the typical non-uniformities, occurring in a cable, e.g. broken filaments, strand welds, cable joints, and edge degradation can be simulated. Also the characteristics of the strands in the cable can be varied from strand to strand.

3. MQE measurement for NbTi cable

Experimental study of MQE was performed on 19-strands keystoned transposed (transposition length $L_p = 62$ mm) cable, where NbTi 0.85-mm diameter wires have Ni or Cr resistive coating of surface (1 µm thickness). For production of the cable was used cabling facility for UNK dipole where cable had 19 wires. The cable, made from uncoated wires with natural oxide on surface, was measured too. Cu/NbTi ratio in the strand is 1.4, critical current density is 2.36 kA/mm² (5 T, 4.2 K), RRR is 115. Cable samples were heated ten minutes at 190°C under pressure of 60 MPa that corresponds to coil curing regime of a superconducting magnet. Experimental values of MQE were obtained in magnetic field up to 6.5 T for different currents through the cable sample. External magnetic field is generated by superconducting solenoid with maximal field of 6.75 T in 60 mm aperture.

Measuring part of cable sample with 40-mm length is pressed up to 60 MPa in a special fixture and immersed into liquid helium bath in the aperture of superconducting solenoid, by such way, that the wide side of the cable is perpendicular to magnetic field. Current through the sample is created by superconducting transformer like [9], which provides current in secondary coil up to 15 kA at primary coil current change on 200A.

In order to generate the heat disturbance in samples, the miniature heaters (like [10]) were used. Such heaters are formed on the surface of certain single wires by following way: approximately 0.6×0.6 mm² cut out is made in the cable insulation and than this hole is filled with carbon paste Epotechny E300. Thin copper foil strip is placed over heater and it serves as a current lead. The strand is used as a return current lead. The resistance of such heater is about half Ohm at 4.2 K. Current through the sample is measured with help of Rogowsky coil and integrator. When current achieves desired value, the short electric pulse from power supply feeds the heater. Pulse duration is 50 µsec but amplitude is controlled. It is well known the MQE remains constant, if duration of energy pulse is 50 - 100 µsec [11]. Voltage drop across the heater and voltage proportional to heater current are measured by digital oscilloscope. Then the heater energy is calculated. The energy, released in heater, is changed step by step consecutively and the threshold energy, which cause quench (i.e. MQE), is found by this way.

The measured dependencies of MQE upon the current are presented in Figure 1 for the cables with Cr coating on the wire surface in different magnetic fields. The measured dependencies of MQE versus ratio $I/I_c$ are presented in Figure 2 for cables with different resistive coatings on the wire surface. This measurement was performed in the external magnetic field of 6 T.

The crossover resistance $R_c$ of cables was also measured. Cable samples were cured in the same regime as was mentioned above. The method, described in [12], was used. The pressure, applied to wide side of cable sample at 4.2 K, was varied in interval from 0 up to 80 MPa. The strong dependence of crossover resistance $R_c$ upon pressure is present at pressure less than 30 MPa, whereas above 30 MPa this dependence becomes weak. Averaged by few samples value of $R_c$ at 80 MPa is equal to 25, 10 and 50 mΩ for cables with Cr coating, Ni coating and cable without strand coating with natural oxide correspondingly.
4. Calculation of MQE for NbTi cable

4.1. MQE of the cable in adiabatic condition
Calculations were made for different electric and thermal contacts in order to understand relation of MQE from electric and thermal contacts between strands. The following parameters are used for the heat transfer of the contact between strands: one case \( x = 500 \text{ W/m}^2\text{K}^{1+b}, \ b = 2 \) and second case \( x = 1000 \text{ W/m}^2\text{K}^{1+b}, \ b = 2.5 \). Calculations were made for \( R_c = R_a \). Values of \( R_c \) are used: 1, 10 and 50 mΩ. The calculations were made for magnetic field of 6 T. Calculated results of MQE versus ratio of a current in the cable to the critical current is shown in Figure 3. Calculations of MQE were made for 18-strands and 20-strands cables (difference is insignificant).

One can see that MQE depends on thermal contact larger then electric contact for the cable for 1 - 50 mΩ \( R_c \) range. Calculation showed absence of current redistributing for the cable with \( R_c = 50 \) mΩ. Weak current redistributing for \( R_c = 10 \) mΩ causes additional heating that decrease of MQE of the cable for \( I/I_c \) more than 0.7.
4.2. Analysis of cooling conditions on the cable MQE

Calculation was made for 7% and 12% volume fraction of helium in cable and 25% strand surface, contacting with helium. A heat transfer for transient cooling is defined by equation $\alpha(T_j, U_j) = a_{trans} \cdot (T_j - U_j)$. Here $a_{trans}$ is 120 W/m$^2$/K$^4$. Calculated results for 6-T magnetic field are presented in Figure 4. MQE strongly depends on coefficient of heat transfer with helium in cable and weakly depends on the helium volume.

![Figure 4](image4.png)

**Figure 4** Calculated MQE (µJ) versus ratio $I/I_c$ for different thermal contacts and volume fraction of helium.

Figure 5 shows the calculated and measured values of MQE versus ratio $I/I_c$. There is an agreement between calculations and experimental results for case of heat transfer between strands with $x = 500$ W/m$^2$/K$^{(1+b)}$, $b$=2 and for $a_{trans}$ is 200 W/m$^2$/K$^4$. MQE for accelerating magnets has to be order of magnitude of 1 mJ [13]. Cables with resistive coatings have sufficient stability for $I/I_c$ about 0.5. Despite of agreement between calculated and experimental results, the model of heat transfer to helium in cable should be improved.

![Figure 5](image5.png)

**Figure 5** Calculated and measured MQE (µJ) versus ratio $I/I_c$. 

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5. Conclusions

- The apparatus for MQE measurements of high-current (up to 15 kA) superconducting cables were created to study short samples in magnetic fields up to 6.5 T. Electric contact resistance measurements showed that cables with Ni and Cr coatings have $R_c$, which are equal to 10 and 25 m$\Omega$ accordingly. Cable with natural oxide coating has noticeable dispersion of $R_c$ values with 50 m$\Omega$ average value. MQE of these cables is the same up to $I/I_c = 0.6$. At $I/I_c > 0.6$ the cable with Cr coating has MQE by factor two higher than one with Ni coating.

- Transient non-linear multiphysics numerical model was developed. Calculated results determine that MQE of cables with coating of strands depends appreciably on thermal resistance between the strands and heat transfer ones with helium in cable. This research showed that cables with studied coatings of strands have sufficient stability.

Acknowledgments

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