STUDY OF ELECTRODYNAMIC AND THERMODYNAMIC MECHANISMS INFLUENCING STABILITY OF SUPERCONDUCTING RUTHERFORD CABLE

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Abstract

Stability for superconducting fast-cycling dipoles and quadrupoles plays an important role. A feature of a complex network of strands and strand-to-strand contacts, current distribution in the network has to be taken into account for superconducting cables. 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 a current redistribution in strands, discontinuities and inhomogeneity, the initial heating in strand, and as a result occasional quench recovery or runaway quench propagations.

Results for the minimum quench energy for cables with core are presented and dependence the minimum quench energy from various parameters of cable is discussed.

INTRODUCTION

Russia expressed interest in the international project FAIR participation [1]. At the moment, IHEP's main tasks are to develop a design of the main quadrupole [2] for the SIS300 ring.

The main quadrupole requirements are as follows: 45 T/m central gradient; 10 T/m/s the field ramp rate; 10 T/m injection field. Maximal magnetic field in the coil is 3.5 T, the operating current I_{op} is 6.26 kA [2], working point at 70% along the load line.

As the given magnet is fast-cycling, it is necessary to have a cable with low losses and simultaneously with a good redistribution of currents between strands of the cable at a quench. For this purpose Rutherford cable has a core decreasing losses in a perpendicular magnetic field and strands, coated by a 0.5 μm thick Staybrite with low resistance for good redistribution of currents between strands.

The thickness of the core is 25 μm and the width is 6 mm. The core is made from an annealed 316L stainless steel foil. The cable with 19 strands is fully keystone, it has the 8.25 mm wide and the average thickness of 1.447 mm. The transposition length is 60 mm, all parameters are presented in [2].

The stability of the superconducting cable against local disturbance is described in general by a curve, presenting the Minimal Quench Energy MQE, as a function of the current I or ratio the current to the critical current I/I_c. If there is current redistribution between strands of cable, normally these curves exhibits a sharp 'kink', separating two distinctive stability regimes. The current, at which the 'kink' occurs, is called I_{kink} [3, 4, 5]. Above the 'kink' MQE of the cable is equal to the single strand MQE. Below I_{kink} MQE of the cable can be more than two orders of higher than the MQE of a single strand, this current redistribution increases stability. In order to improve the stability, a shift of the 'kink' to higher current and an increase of the quench level left from the 'kink' is highly desirable. This can be achieved by increasing heat transfer to helium and the Residual Resistance Ratio of the copper RRR, and decreasing contact adjacent resistivity R_a and thermal contact.

APPROACH FOR ANALYSIS OF MQE

For the study of MQE the cable was fabricated with properties, almost the same as the original cable of quadrupole has. The cable used three types of strands with different critical current density: 2548, 2632 and 2406 A/mm^2 (5T, 4.2K), Cu/NbTi ratio of the cable is 1.45, RRR differs from 110 to 200.

Further for MQE analysis the current of the cable is used instead of the ratio I/I_c as strands have the different critical currents, so it is difficultly to calculate correctly the ratio of the current to the critical current of the cable. Other reason is impossibility to compare the working point on the load line with I_{kink}/I_c, as MQE measurements were carry out at a constant magnetic field. MQE is possible to study numerically as a function of magnetic field for turn in the high magnetic field of the magnet [5]. In this case one can compare the working point on the load line with $I_{kink}/I_c(B)$ but it is difficult to compare with measurement dates I_{kink}/I_c (constant magnetic field, therefore constant I_c)

The measurements of MQE were carried out in liquid helium (pressure of 1 atm., temperature of 4.3 K), so it is necessary to compare measured and calculated results. General experimental arrangements are described in [6].

Simulations of MQE were performed with code, developed in IHEP [7] and the CUDI program, developed in CERN [8].

These codes consist of electrodynamics and thermal parts. For electrodynamics part basic input parameter is a contact resistivity, which can be measured. For cable with core the contact adjacent resistivity R_a is about 0.2 mΩ and the crossover resistivity R_c is larger than 20 mΩ [9].

In thermal part the most difficult is correctly to define a heat transfer through thermal contact resistance between contacting strands and between strands and helium.

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The thermal contact conductivity between contacting strands k_{cont} given by:

$$k_{cont} = f_{cont}\, T^{2.25}. \qquad (1)$$

Here T are temperature of strand, f_{cont} is constant. The contact surface between contacting strands is 150 mm^2 [4].

Heat transfer to Helium I consists of these regimes: the most important regime is the transient cooling regime defined by

$$h_{He} = a_{trans}\left(T_s^4 - T_{He}^4\right) A_{He}\,, \qquad (2)$$

the steady-state Nucleate boiling is defined by

$$h_{He} = a_{nb}\left(T_s - T_{He}\right)^{2.5} A_{He}\,, \qquad (3)$$

and the film boiling is defined by

$$h_{He} = 250\cdot\left(T_s - T_{He}\right) A_{He}\,. \qquad (4)$$

Here T_s and T_{He} are temperatures of strand and Helium, h_{He} is coefficient of heat transfer, a_{nb} and a_{trans} are constants. The contact surface between strand and helium A_{He} is 650 mm^2 [4].

If the transient heat flow into the helium exceeds a certain limit in 20 J/m^2[10], the nucleate boiling regime starts. Nucleate boiling regimes continues until heat flow h_{lim_nb} is reached to 1.5 10^4 Wm^{-2}. Values a_{nb} is $5\cdot10^4$ Wm^{-2}K$^{-2.5}$.

Preliminary simulations of MQE by varying f_{cont} and a_{trans} parameters show that simulated results fit the measured results with f_{cont} = 200 Wm^{-2}K$^{-2.25}$, a_{trans} = 200 Wm^{-2}K^{-4}.

NUMERICAL CALCULATION OF MQE

Calculated current redistribution in the cored cable through R_a is shown, for example, in Fig. 1 and Fig. 2 without quench after current redistribution. Fig. 1 shows numbering of cable strands in the code. Some curves in these Figs are coincided. As an example Fig. 3 shows the current redistribution in the case of quench. The onset of the normal zone is in sixth strand.

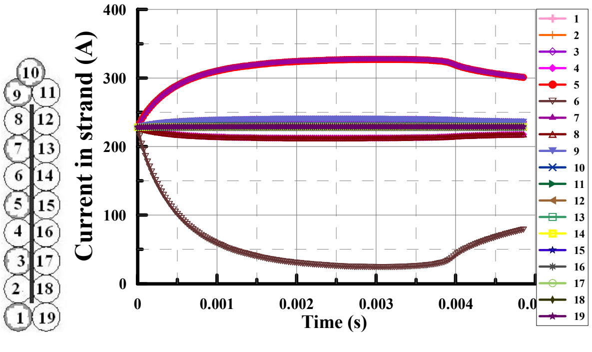

Figure 1: Current in strands of the cable during time. The onset of the normal zone is in sixth strand.

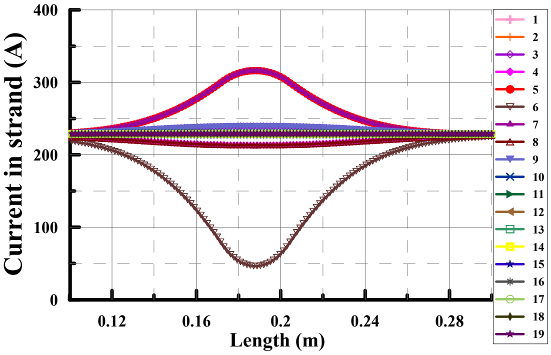

Figure 2: Current in strands of the cable along strands at 1 ms after the onset of the normal zone is in sixth strand.

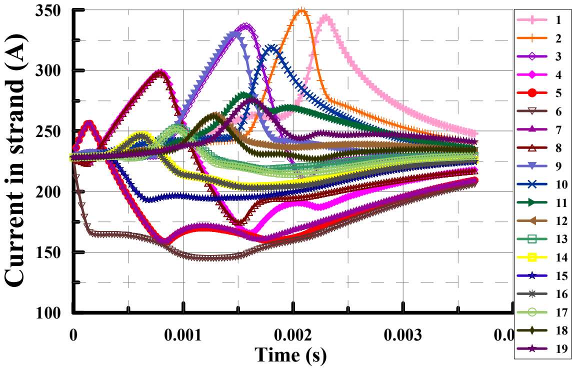

Figure 3: Current in strands of the cable during time. The onset of the normal zone is in sixth strand.

The measured dependences of MQE versus current for cored cable are presented in Fig. 4 for 3.5 T magnetic field (maximal field in the coil of the quadrupole). Also at Fig. 4 the simulated curves for RRR 110 and 200 are shown, current density 2500 A/mm^2 (5T, 4.2K) for all strands.

Using a scaling factor, which is defined by ratio between the effective quench energy and the input pulse energy [11], a good coincidence between measured curve and the simulated curves is received (Fig. 5). Scaling factor is 0.4 after I_{kink} and 0.9 before I_{kink}.

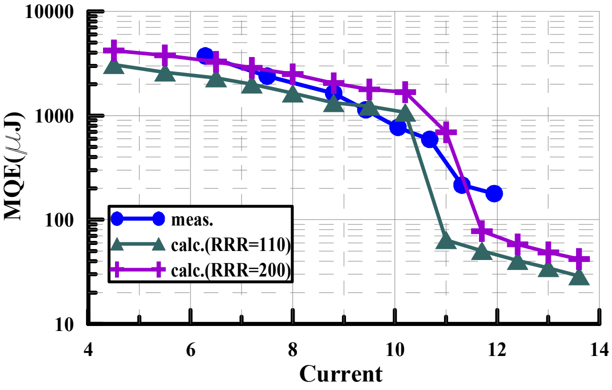

Figure 4: Measured and calculated MQE versus current.

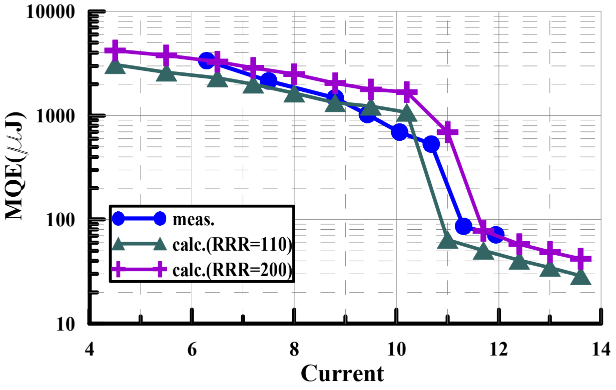

Figure 5: Measured (with scaling factor) and calculated MQE versus current.

Fig. 5 shows that I_{kink} in liquid helium is about 10.5 kA, this value is sufficiently larger than the operating current. For stability of cable I_{kink} have to be larger then I_{op}. The ratio I_{kink}/I_{op} is about 1.6.

In real condition the quadrupole will be cooled by supercritical helium. In this condition the stability is investigated by numerical calculation [5]. The coefficient of heat transfer from cable into supercritical helium is lesser then coefficient of heat transfer from cable into liquid helium, so MQE will be lesser for the cable cooling supercritical helium. MQE of cable, cooled by supercritical helium, is larger then in adiabatic condition.

The ratio of I_{kink}/I_{op} (calculated or measured) at cooling cable in liquid helium is top limit of this ratio for a magnet. I_{kink}/I_{op}, calculated for adiabatic condition, is bottom limit. If $(I_{kink}/I_{op})_{adiab} > 1$ for a magnet it will be have a good stability.

The simulated curves of MQE for RRR 110 and 200 with f_{cont} = 200 Wm^{-2}K$^{-2.25}$ are shown in Fig. 6 for adiabatic condition. Fig. 6 shown curves calculated both the program CUDI and code, developed in IHEP.

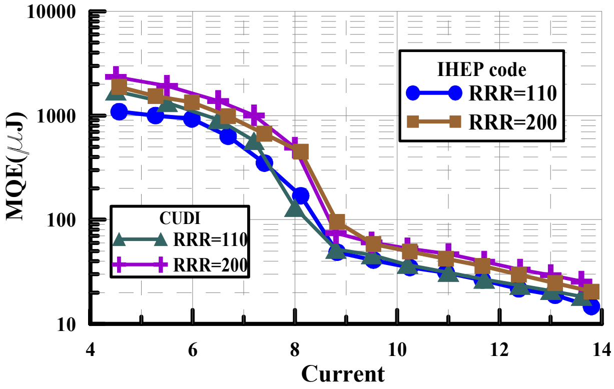

Figure 6: Calculated MQE versus current for adiabatic condition.

One can see I_{kink} in adiabatic condition is about 8 kA, this value is larger than the operating current. The ratio $(I_{kink}/I_{op})_{adiab}$ is about 1.25. It means that the cored cable, having the next parameters: RRR > 110, $R_a \approx 0.2$ mΩ, $R_c > 20$ mΩ and $f_{cont} \approx 200$ Wm^{-2}K$^{-2.25}$ for the quadrupole will have a good stability in the real conditions (cooling supercritical helium, B_{max} = 3.5 T).

CONCLUSION

IHEP has developed the design of the quadrupole for the SIS 300. Keystone 19-strand Rutherford cable with core is the preferred choice for the quadrupole. For estimation of stability of these cable we used ratio I_{kink}/I_{op}. This ratio has to be lager 1. For liquid helium I_{kink}/ I_{op} is about 1.6. For adiabatic condition $(\mathrm{I_{kink}/I_{op}})_{\mathrm{adiab}}$ is about 1.25. This magnet will have a good stability in real conditions (cooling supercritical helium, B_{max} in the coil is 3.5 T).

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