METHODS FOR REDUCING CABLE LOSSES IN FAST-CYCLING DIPOLES FOR THE SIS300 RING

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INTRODUCTION

One of the main tasks in the design of fast-cycling superconducting (SC) dipoles is minimization of heat losses arising in the magnet during its energising / de-energizing. Three designs of a SC dipole for the SIS300 ring were studied, as the first step [2]. In general, these designs differ primarily in coil restraint collar thickness and therefore also in the iron yoke contribution to the total magnetic field. The first design has 45 mm thick collars, which restrain the entire electromagnetic load during coil energizing.. The 30 mm thick collars of the second design restrain the coil during magnet assembly and cool-down. Afterwards, the iron yoke serves as the restraint during magnet energizing. The iron yoke in the third geometry is placed close to the coil and serves as a collar and as a restraint against magnetic forces. In the first design, the iron contributes the least to the magnetic field and therefore this design requires the most superconductor volume. This leads to the highest coil heating losses, which one would like to reduce.

MAIN CHARACTERISTICS

Table I shows the main characteristics of SC strands.

Table 1. Main Characteristics of SC Strand.

Wire diameter, mm	0.65
Ti composition, %	47
Diameter of filaments, μm	3.5
Number of filaments	14485
Twist pitch, mm	4.0
Resistive barriers	No
Copper/Superconductor ratio	1.38
Ratio $\rho_{300}/\rho_{4.2}$	¥70
Strand coating	Oxide
Critical current (5 T, 4.2 K), A	375
Critical current density, kA/mm^2	2.7

The main parameters of the three designs under consideration are presented in Table 2. All losses were calculated for a triangular cycle 0 – 6 T –0 with *dB/dt*=1 T/s.

GENERAL CONSIDERATIONS

The heat losses in the coil increase with increasing cable width and strand number, as is shown in Figure 1.

As one can see from Figure 1, cable losses grow much faster than other loss components and become a significant loss contribution as the number of strands increases. Below, we consider ways to suppress cable losses.

Table 2. Main Parameters of Considered Geometries.

Geometry	I	II	III
Collar thickness, mm	45	30	10
Strand number in cable	38	35	30
Bare cable width, mm	12.80	11.70	9.91
Cable thickness, mm	1.264	1.273	1.289
Total turn number	91	90	89
Operating current, kA	4.98	4.78	4.48
Inner iron radius, mm	121.4	104.2	80.6
Iron thickness, mm	158	138	140
Hysteresis losses in coil, J/m	81	74	57
Matrix losses in coil, J/m	19	18	14
Cable losses in coil, J/m	65	42	23
Total losses in coil, J/m	165	134	94
Losses in iron, J/m	25	31	30
Total losses in magnet, J/m	190	165	122
Stored energy in magnet, kJ/m	245	227	224

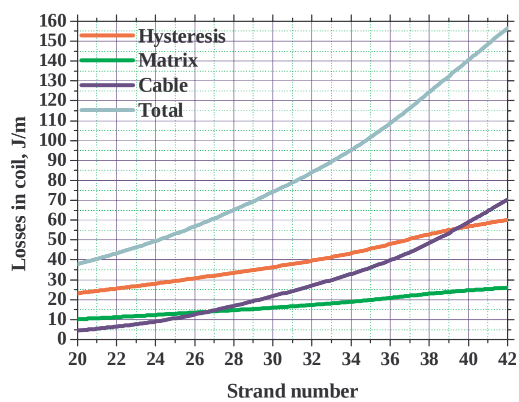

Figure 1. Losses in coil versus strand number in cable.

Cable losses per unit volume P_C are determined by:

$$P_C = \frac{p^2}{16}\left(\frac{8}{15}\frac{\alpha^2 \dot{B}_\perp^2}{\rho_c} + \frac{1}{3}\frac{\dot{B}_\perp^2}{\rho_a} + \frac{1}{4}\frac{\dot{B}_\parallel^2}{\alpha^2 \rho_a}\right).$$

Here (using nomenclature [3]): $p = 4c/tanq$ is transposition length of the cable; $2c$ and $2b$ are cable width and thickness and q is the angle of transposition; $a = c/b$; r_c and r_a are the crossover and adjacent resistivities of the cable; $B_{\wedge}$ and $B_{||}$ are the transverse and parallel to the wide cable side components of magnetic field ramp rates.

So, there are several ways to decrease cable losses, some of which will be discussed below.

Decreasing of Transposition Length

Decreasing the cable transposition length can be achieved by increasing the transposition angle q. At present, the IHEP cabling machine has a limit of 15± for *q*. For example, if *q* could be increased up to 20±, we would get a decrease in cable losses by a factor of $(\tan 20±/\tan 15±)^2$ = 1.85. With that, we lose in longitudinal component of current, but its drop is insignificant: dI_z ~ 1 – *(cos20±/cos15±)* = 0.03.

Reduction of Cable Width/Thickness Ratio

Reduction of cable width/thickness ratio can be achieved by decreasing the cable width $2c$ and by increasing the cable thickness $2b$. Both these ways can be realized by increasing the strand diameter d. Influence of d variation on total cable losses was described in [4]. In any case, increasing the strand diameter will not require additional investment, as magnets for the SIS300 will be fabricated with a special new superconductor.

Decreasing Strand Number in Outer Layer

The outer layer is in a lower magnetic field, in comparison with the inner layer. So, the critical temperature T_C in it is much higher. Hence, it is possible to lower this critical temperature to level of the inner layer by cutting down on the strand number in the cable of the outer layer. Calculations showed (Figure 2) that this operation is ineffective because the main part of the losses is in the inner layer. In addition, the different widths of the cables require the presence of a soldered joint between them, in which appreciable additional heat loads will appear.

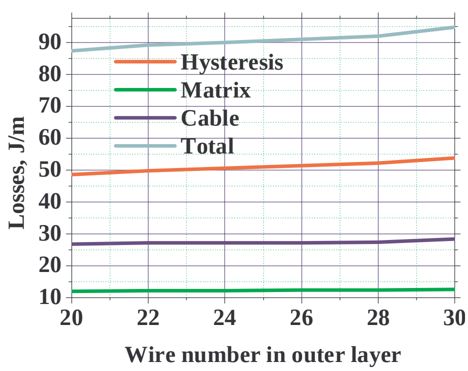

Figure 2. Heat losses versus strand number in outer layer.

Crossover and Adjacent Resistivities

Suitable values of the above mentioned cable parameters could be achieved through either the selection of a resistive insulation coating of the SC wire strands or by inserting a core into the cable. Of course, either both components of the resistivity or at least one of them must have an upper limit in order to allow current sharing in the cable for magnet stability. This limit depends on quality of the SC wire and on the quality of magnet manufacturing. Thus, determining this upper limit can be determined only experimentally with short magnet models, which would be very expensive.

A short model of a 4-T one layer SC dipole, based on cored cable, was produced and tested in BNL [5]. Further a cable design without core will be considered for the SIS300 dipoles.

Different materials can be used as cable strand coatings. Figure 3 illustrates the resistivity for some materials [6]. One can see that the Cr gray coating has at least an order of magnitude greater resistivity than Cu non-coated (natural oxide). On the other hand, the formation of an oxide coating can be produced by different methods. Some of them allow one to reach higher specific resistance and to get a more stable coating in comparison with natural oxide. The oxide coating has difficult-to-control thickness, and consequently, resistivity. Taking this into consideration, the *Ni* and *Cr* coatings can be applied, with the required thickness of 1, 2 or 3 mm. Moreover, all above considerations require thorough cable R&D.

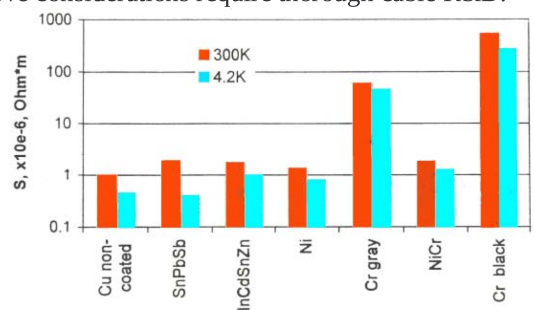

Figure 3. Resistivity for materials of strand coating.

Three-Layer Design

Advantages:

- Decreasing of the strand number in the cable. It implies the decreasing of the cable width and decreasing of the a coefficient, what leads to a cable loss reduction.
- There is a possibility to increase T_C of the coil by means of increasing the number of strands in the cable. It is a compromise with the preceding point.

Disadvantages:

- Design complication. It rises in magnet price.
- It is assumed; the 2-layer coil will be wounded with a single piece of cable, without any soldered joints between the inner and the outer layers. Calculations show the presence of the soldered joint in the coil increases heat losses, what makes magnet training worse. Three layer coils requires the presence of a soldered joint between the middle and outer layers, as the third layer must be wounded with a separate piece of cable.
- The inner turn of the third layer must be moved outside of the coil, in order to either produce the soldered joint or to energized the coil. This fact essentially complicates the collar design as well as reduces the reliability of obtaining adequate coil stress. It causes a fall of the magnet efficiency. In addition, integral field quality is deteriorates by this turn.
- Basically, it is possible to wind a 3-layer coil with a single piece of cable, but then the straight part of the third layer must be longer than the overall length of the middle layer. It results in a lengthening of the end parts and in reduction of the magnetic length.
- To have a magnet that worked reliably, each layer of the coil must have an optimal preload. In case of the 3-layer coil it is more difficult to realize this requirement.

- The narrow cable can be a cause of excessive training of the dipole. IHEP had experience with such cable [7]. The first short dipoles with cold iron had been produced with 16-strand cable. They had very bad training and did not reach their short sample current. The ponderomotive forces change weakly with cable width, but pressure has a strong dependence on this parameter. So, the turn motion during energizing/de-energizing of the dipole is large enough to cause coil heating through frictional forces and consequently a quench.
- The mass of the magnet and overall dimensions grow.

COMPUTER SIMULATION

Table 3 presents loss calculations for different designs of SC cable for the first geometry: design 1 is the initial cable design; 2 – Cr coating; 3 – cored cable; 4, 5, 6 – increased strand diameter; 5 – increased transposition angle; 6 – 3-layer dipole. All loss values are presented for a triangular cycle 0 – 6 T – 0. It should be noted that the values of crossover and adjacent resistivities for Cr coatings were chosen low enough in order to allow a possibility of current sharing between strands. The losses for the 3-layer magnet were calculated without taking into account losses in two soldered joints.

Table 3. Results of Loss Calculations for Different Variants.

Design	1	2	3	4	5	6
Number of layers	2	2	2	2	2	3
Strand diameter, mm	0.65	0.65	0.65	0.85	0.85	0.85
Twist pitch, mm	4.0	4.0	4.0	5.2	5.2	5.2
Core	No	No	Yes	No	No	No
Strand coating	Oxide	Cr Grey	Staybrite	Oxide	Oxide	Oxide
Crossover resistivity, mWμm	5	10	92	5	5	5
Adjacent resistivity, mWμm	5	10	0.074	5	5	5
Total turn number in the coil	91	91	88	70	70	98
Strand number in turn	38	38	39	28	28	20
Bare cable width, mm	12.80	12.80	13.10	12.17	12.51	8.47
Bare cable thickness, mm	1.120	1.120	1.170	1.486	1.486	1.528
Transposition angle, deg.	15	15	15	15	20	15
Transposition length, mm	95.5	95.5	97.8	90.8	68.7	63.2
Core thickness, mm	—	—	50	—	—	—
Operating current at m = ¶, kA	4.95	4.95	5.14	6.38	6.41	4.54
Critical temperature at m = ¶, K	5.42	5.42	5.37	5.40	5.40	5.43
Hysteresis losses, J/m	71.9	71.9	69.7	69.9	71.9	70.2
Matrix losses, J/m	16.8	16.8	16.2	27.7	28.5	28.0
Cable losses, J/m	72.9	36.4	28.6	32.9	20.4	7.4
Total losses, J/m	161.5	125.1	114.5	130.5	120.7	105.6

Analysis of Table 3 shows that the 2-layer coil will be able to have minimal losses, if the following parameters will be used (the most optimistic variants) (Table 4):

Table 4. Losses with the Most Optimal Parameters.

Parameters		
Strand diameter, mm	0.85	0.85
Strand coating	Cr Grey	Staybrite
Twist pitch, mm	4	4
Transposition angle, deg.	20	20
Cable design	Without core	With core
Losses, J/m		
Hysteresis	71.9	70.0
Matrix	16.8	16.4
Cable	10.2	12.6
Total	98.9	99.0

One can see the both variants have the same total losses and this value is lesser than it has in Geometry III.

CONCLUSION

As a consequence of consideration of different ways of cable loss suppression, two equivalent cable designs are chosen. But it is clear all calculations should be confirmed by experiment and real measurements. The final choice has to be made only after careful cable R&D and production of several short models. Of course the optimal choice of the cable is necessary for handpicked geometry in future from three concerned for the GSI geometries for detail further development.

REFERENCES

[1] http://www.gsi.de/GSI-Future/cdr/.

[2] L.Tkachenko et al. Comparison of three Designs of Wide Aperture Dipole for SIS300 Ring. This Conference.

[3] M.N. Wilson, MNW Report GSI 18-1, 7 Feb. 2004.

[4] V.E. Sytnikov. Minimisation of Coupling Losses in Multiwire Superconducting Cables. IEEE Transactions on Magnetics, Vol. 27, No. 2, March 1991, p.2491

[5] P. Wanderer et al., Initial Test of a Fast-Ramped Superconducting Model Dipole for GSI"s Proposed SIS200 Accelerator, presented on PAC, 2003, USA,

[6] V.E. Sytnikov. Private communication,

[7] A.I. Ageev et al. Superconducting Cold Iron Dipole Magnet for UNK, Proc. of the ICFA Workshop on Superconducting and Cryogenics, BNL, 1986, p.199.