EXPERIENCE WITH DIFFERENT CONSTRUCTIONS OF SUPERCONDUCTING CORRECTOR MAGNETS FOR THE LHC

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Abstract

In the framework of the LHC magnet development program, CERN has tested different design principles on superconducting corrector magnet prototypes. In this paper we review experience with the manufacturing and testing of sextupole and decapole spool-correctors featuring cosine-Θ type of coils, made of double width in order to halve the number of the coils. The two-layer racetrack coils have been wound from a rectangular NbTi-wire without using any end spacers. The design variants with and without azimuthal pre-stress have been built. The expected performance from the calculations has been compared with the measured training of the magnets both at 4.2K and 1.9K.

1 INTRODUCTION

The are some 60.000 spool-corrector coils to be wound, including a foreseen octupole winding MCO nested inside the decapole spool-piece MCD. By making the coils double width it is possible to halve their number eg five coils per decapole instead of ten. The principle is presented in Fig. 1. This design simplifies the inter-coil connections, since in addition to their reduced number, which means reduced resistive heating power into He-bath, no wire crossings are needed. However, the drawback of this design option is a higher peak field, due to the increased number of turns in the coil ends. In the case of the sextupole this would mean an increase of the peak field from 2T to 2.5T and correspondingly a rise of the working point from 40% to 45% (550A, 1.9K), which is still very a low value. The first normal harmonic can be mastered by adjusting the height of the coil block and the skew field errors induced by the asymmetric coil ends can be compensated by changing the position angle of the coil block in the straight part.

2 DESIGN VARIANTS

2.1 Coils

In order to exploit as much as possible the existing tooling and parts, we have not tried to optimise the field quality of the magnets. The purpose of these models was above all to learn the influence of the different constructions on the training. The main characteristics of the different models are presented in the Tables 1 and 2.

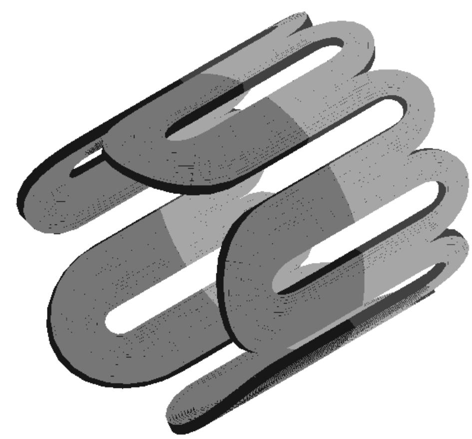

Figure 1: Principle of 5-coil and 10-coil decapole left and right respectively

2.1.1 Decapole types

For the MCD_A5B we used the LHC sextupole spool-piece coils, which were wound and cured as described in [1,2]. For the MCD_B5B we used sextupole coils too but removed the central posts after curing. The coils cover an ideal azimuthal angle of 60° but due to a too wide central post, have only 13 turns in the azimuthal direction instead of the optimal 16 turns.

2.1.2 Sextupole types

The shape of the central posts used in the double width sextupole coils is also identical with the ones used in the standard MCS coils. The coils feature two radial layers each with 29 azimuthal turns instead of the original 13 turns covering an angle of 110°, which is larger than the optimal angle of about 100°. Owing to their large angle, these coils are more demanding to wind than the standard coils. Although we managed to wind them with a simple hand driven machine, they might be inconvenient for the serial production. The central post material differs from magnet to magnet. The coils of the MCS_IP3G, MCS_AB3F and MCS_S1 have been wound around the standard MCS central post machined of G11-tubes. For MCS_S2 we used central posts machined of Ultem 2400, which is an attractive material for big quantities, since it can be moulded. The central post of the MCS_S3 are manufactured by resin transfer moulding (RTM) impregnating a stainless steel insert wrapped with a fibre glass cloth in Stycast 1266. The end saddles of all the coils were machined of G11-tubes.

2.2 Magnets without pre-stress

In the case of a magnet featuring the full number of coils, each coil block feels a radial and an azimuthal em-force component. The voids between neighbouring coils need to be filled with shims in order to counterbalance the opposite azimuthal force components between coils. In the double width coils, however, the azimuthal force components compensate each other inside each coil block leaving only a radial external force. In this case the azimuthal pre-stress may be not crucial as long as the coils are supported properly radially.

To check the feasibility of this design option, two decapoles and two sextupoles have been built where the individual double width coils are screwed via the central posts into an iron tube. There is a 2.5mm thick G11-segment glued on the coils to reinforce them and to act as ground insulation to the surrounding iron yoke. The inter-coil connections are made on the connection plate fixed on the end of the iron tube.

Table 1: Parameters of experimental magnets.

	MCS	MCD
Overall length	170mm	155mm
Number of coils	3	5
Turns per coil	2×29	2×13
Gradient	1863T/m^2	1.54×10^{6}T/ m^4
Peak field 3D	2.5T @ 550A	2T @ 550A
I quench 4.2K / 1.9K	879A / 1200A	960A / 1310A
ID / OD of coil	56mm / 66mm	
Wire bare	1.13mm×0.606mm	
Insulation (PVA)	60µm	
Cu/Sc ratio	1.6	
RRR	100	
Filament Ø	7-10µm (75µm MCS_IP3G)	
Icr (5T,4.2K)*	650A ⊥, 740A // to broad face	

* Lowest values reported by manufacturer

2.3 Magnets with pre-stress

In the magnets with pre-stress the coils are assembled as a complete tube by gluing G11-wedges in the voids between the adjacent coils. The coil assembly is then wrapped in a G11 pre-preg cloth, which is cured and then turned to the desired dimensions as described in [1]. In MCS_IP3G1 the azimuthal pre-stress is transferred from the aluminium cylinder in to the coil by scissor type of laminations [3]. The radial interference at room temperature between the aluminium shrinking cylinder and the yoke assembly around the coils was 0.07mm. According to a FE-model this equals to a maximum azimuthal compression of about 40MPa and 65MPa at room and liquid He-temperature respectively. The yokes of MCS_S1, MCS_S2 and MCS_S3 are each composed of six iron sectors slitted from a tube. Due to almost homogenous contact with the bandage also at low temperatures, the sectors create less bending moments in the coils than the round scissors laminations. At room temperature, the radial interference between the sectors and the shrink ring is 0.05mm. The calculated azimuthal stresses in the coil blocks are reported in the Table 2.

Table 2: Design variants and calculated azimuthal stresses in coil blocks

Magnet	Central Post	Max azim stress in coil @ 4.2K 0A/600A	Yoke Type
MCD_A5B	G11	+36 / +36MPa	Tube
MCD_B5B	None	+36 / +36MPa	Tube
MCS_AB3F	G11	+36 / +36MPa	Tube
MCS_IP3G1	G11	-65 / -61MPa	Lamin
MCS_IP3G2	G11	+36 / +36MPa	Tube
MCS_S1	G11	-44 / -33MPa	Sector
MCS_S2	Ultem	-37 / -28MPa	Sector
MCS_S3	RTM	-55 / -48MPa	Sector

3 DISCUSSION ON TRAINING

3.1 General

Training of different models is shown in the Fig. 2. For comparison typical training curves of the present 6-coil sextupole and 10-coil decapole are also presented. The short sample limit of the used wire varies between different lots, which is the reason why some magnets reached higher critical current than calculated.

3.2 Wire stability

MCS_IP3G1 coils have been wound with a wire used for the first winding trails, featuring a filament diameter of 75µm. The magnet showed much training and reached a plateau at a level of 800A at 4.2K, which is about 80A below the calculated critical current. When the magnet was further tested at 1.9K, it reached plateau at 780A, which was surprisingly lower than at 4.2K. The coils of the magnet where cut from the assembly and mounted inside an iron tube, without any azimuthal pre-stress. The new assembly MCS_IP3G2 showed similar training behaviour reaching a lower current at 1.9K than at 4.2K. This confirmed that the magnet performance was not limited by the mechanical structure but by the superconductor itself. The maximum diameter of a sc-filament, which is stable against flux jumps (dynamic stability) is given by the equation:

$$d_{fil} < \sqrt{\frac{k_{sc}\cdot\lambda\cdot(T_c - T_o)}{\rho_{cu}} + c_w\frac{(T_c - T_o)(1+\lambda)}{\mu_0}}\;\frac{\pi}{J_c}$$

where λ is the matrix to superconductor ratio, c_w the mean volumetric specific heat capacity of the composite wire and ρ_{cu} resistivity of the copper matrix. J_c is the critical current density at the operating temperature T_o and T_c the critical temperature of the wire at the operating field and current. The material data can be found from [4-7]. The

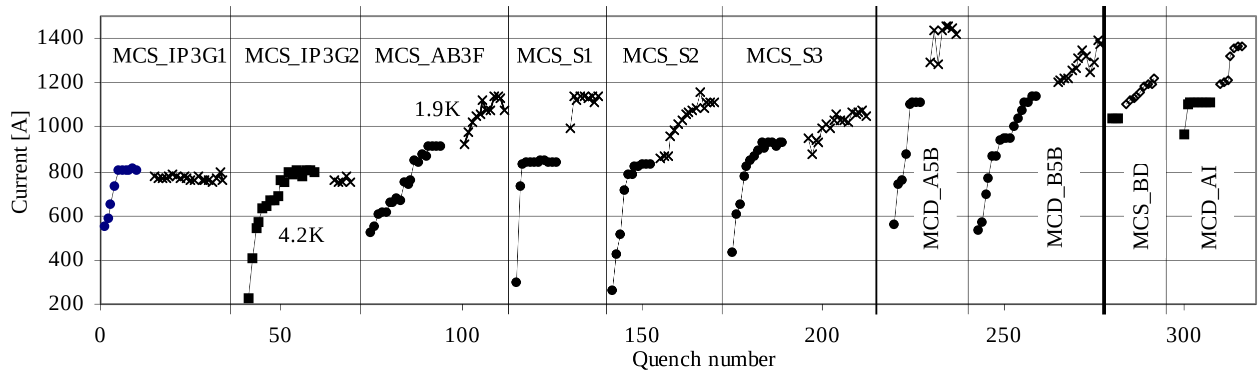

Figure 2: Training of sextupole and decapole models with double width coils. MCS_BD and MCD_AI are standard versions featuring 6 and 10 coils respectively. Wire used in MCS_IP3G1&2 is unstable due too big sc-filaments.

thermal conductivity of the superconductor below critical temperature is approximated by :

$$k_{sc} = 0.0066 \cdot T_{op}^{\;2.02} \frac{W}{m \cdot K}$$

From Fig. 3, which presents the critical filament diameter as a function of the operating temperature at 800A and 3.68T, can be clearly seen that the critical current is limited by the too big and therefore unstable filaments.

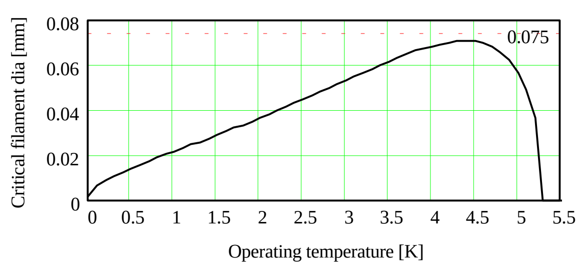

Figure 3: Critical filament diameter as function of temperature in MCS_IP3G (Iop=800A, B=3.68T)

The fact that the critical filament diameter at 1.9K predicts a much smaller critical current than actually can be reached, might be explained by the rapidly increasing specific heat with the increasing temperature, which helps the superconductor to recover. The filament diameter used in all the other models is 7-10μm, and clearly stable against flux jumps both at 4.2K and 1.9K.

3.3 Azimuthal pre-stress

From the three magnets equipped with iron sectors and an aluminium shrinking ring, MCS_S1 with G11-central posts, showed a very fast training. It reached the critical current at 4.2K after two quenches and at 1.9 K after one additional quench. The two other ones with the alternative central post materials trained much more. However, in the case of MCS_S2 most quenches occurred in the same pole, which points to a possible defect in the coil.

The MCD_A5B is the only magnet without azimuthal pre-stress, which showed fast training. Whereas the decapole MCD_B5B, which features coils without central posts as well as the sextupole MCS_AB3F exhibited many training quenches. This can be explained by different contraction properties of the used materials. The azimuthal contraction factor of the coil higher than that of the G11-segments glued on them introduces tensile stresses up to 35MPa in the coil blocks. As a result the coil curves and only the centre line of the coils stays in contact with the surrounding yoke, the maximum radial gap being about 0.15mm and 0.05mm in the case of sextupole and decapole respectively. When energised, the em-forces push the coil radially towards the iron cylinder exerting a bending moment into the coil block and further increasing the azimuthal tensile stresses.

4 CONCLUSIONS

All the magnets without azimuthal pre-stress in the coils, except decapole MCD_A5B, showed a long training before attaining the critical current due to tensile stresses in the coils. MCS_S1 featuring coils wound around G11-central posts and an azimuthal pre-stress trained very quickly. The wire used in the MCS_IP3G1 was unstable against flux jumps due to the big filament size, and the critical current of the magnet was 80A lower than the calculated one at 4.2K. The double width cosine-θ type of coils, with azimuthal pre-stress is a feasible and possibly attractive way to reduce the number of the coils and to simplify the design of small LHC corrector windings.

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