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The Development of the Inner Triplet Dipole Corrector (MCBX) for LHC

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A prototype of the MCBX correction dipole magnet is being built in industry. It features a horizontal dipole nested inside a vertical dipole The coils of the 0.6 m long single-bore magnet are wound with 7 or 9 rectangular superconducting wires pre-assembled as flat cables. As the end fields contribute for more than 50 % to the field integral an optimisation in 3D was required. The impregnated coils containing CNC-machined end spacers are pre-compressed with an aluminium shrinking cylinder. The yoke consists of scissor-laminations to back up the coil rigidity and to centre the coil assembly. These laminations move inward during the cooldown and the movement is blocked at a pre-defined temperature building-up a circumferential stress in the stainless steel outer shell. This paper describes the magnetic and mechanical design of this magnet. The expected performance from the calculations is presented. The assembly procedure is reviewed and the experience with the 250 mm long mechanical model is reported.

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***Abstract* — A prototype of the MCBX correction dipole magnet is being built in industry. It features a horizontal dipole nested inside a vertical dipole The coils of the 0.6 m long single-bore magnet are wound with 7 or 9 rectangular superconducting wires pre-assembled as flat cables. As the end fields contribute for more than 50 % to the field integral an optimisation in 3D was required. The impregnated coils containing CNC-machined end spacers are pre-compressed with an aluminium shrinking cylinder. The yoke consists of scissor-laminations to back up the coil rigidity and to centre the coil assembly. These laminations move inward during the cooldown and the movement is blocked at a pre-defined temperature building-up a circumferential stress in the stainless steel outer shell. This paper describes the magnetic and mechanical design of this magnet. The expected performance from the calculations is presented. The assembly procedure is reviewed and the experience with the 250 mm long mechanical model is reported.**

I. Introduction

To compensate for the misalignment of the quadrupoles (MQX) in the LHC [1] low-β triplets in total 16 combined horizontal and vertical corrector dipoles are required. As a part of the LHC magnet development program a prototype of the MCBX correction dipole magnet, whose parameters are presented in Table I, has been designed by CERN and built by Danfysik A/S. The 0.6 m long single-bore magnet consists of a horizontal dipole nested inside a vertical dipole, wound with 9 and 7 rectangular superconducting wires respectively, pre-assembled as flat cables.

The magnetic and mechanical optimisation of this 0.6 m long magnet was carried out linking together different electromagnetic software and CAD/CAM systems described in [2]. Most of the design variables used in optimisation had to be addressed in 3D. To verify the assembly procedure a 250 mm mechanical model was assemble from two half inner coils and two half outer coils and its dimensions were measured warm and at 77K. These measurements were used to tune the FE-model and to define the assembly parameters for the prototype magnet. The prototype magnet has been completed and cold tests are starting at CERN.

II. Magnetic Design

The nested dipole coils are individually powered and can produce both a horizontal and a vertical field. The nominal field integral is 1 Tm in any direction, which gives a maximum kick angle of 42.8 μrad at 7 TeV. The working point on the load-line for the LHC corrector magnets with vacuum impregnated coils is typically below 60 %.

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TABLE I

Main Parameters of MCBX-Dipole Corrector

	Horizontal dipole	Vertical dipole	
Magnetics			
Nominal strength	3.3	3.3	T
Integrated field	1.2	1.1	Tm
Magnetic length	0.37	0.34	m
Peak field in coil	4.4	4.8	T
Geometry			
Overall length	0.55		m
Coil length	0.5	0.5	m
Coil inner diameter	90	123.7	mm
Coil outer diameter	119.7	146.8	mm
Yoke inner diameter	200		mm
Yoke outer diameter	470		mm
Electrics			
Nominal Current	0-511	0-599	A
Number of turns/coil	414	406	
Stored energy/magnet	17.9	25.2	kJ
Self inductance/magnet	0.137	0.140	H
Conductor			
Cross section	1.6	1.6	mm^2
Cross section(metal)	1.3	1.3	mm^2
Copper/NbTi ratio	1.6	1.6	
Filament diameter	10	10	μm
Twist pitch	18	18	mm
Current density (NbTi)	1022	1198	A/mm^2
Margin to quench	51.7	46.2	%

A. *Field quality*

The tolerances for the multipole components [3] are extremely tight in the low-β triplet, where β-functions rise to over 4000 m to achieve maximum luminosity at full energy. The expected systematic and random components at a reference radius of 10mm are presented in Table II. The skew terms with respect to the main field of each coil are introduced by the cross-over conductors in the connection end together with the transitions between the end blocks. A sensitivity analysis was carried out in 3D to find the random errors arising from the mechanical tolerances. The following perturbations were introduced for one coil-block at a time and the different cases were summed up quadratically (acceptable range in parenthesis):

1) Positioning angle of the conductor block (±0.064 deg)
2) Inclination angle with respect to the X-axis (±0.1 deg)
3) Radial displacement (±0.05 mm)
4) Block width (±0.1 mm)
5) Axial shift in the ends (±0.2 mm)

TABLE II

EXPECTED FIELD QUALITY OF INNER AND OUTER COILS NORMALIZED TO THEIR DIPOLE COMPONENTS , $b_n=B_n/B_1 \times 10^4$ (b-TERMS VERTICAL, a-TERMS HORIZONTAL FIELD COMPONENTS)

	Systematic Inner	Random Inner	Systematic Outer	Random Outer
b1	26.7344	3.5317	10000	
b2	-	1.3826	-	5.704
b3	2.2308	0.3053	0.1124	0.1474
b4	-	0.0780	-	0.0203
b5	0.0590	0.0162	0.006	0.0599
b6	-	0.0037	-	0.0006
b7	0.0033	0.0008	0.0162	0.0088
b8	-	0.0002	-	0.0000
b9	0.0000	0.0000	0.0000	0.0001
b10	-	0.0000	-	0.0000
b11	0.0000	0.0000	0.0000	0.0000
a1	10000		38.5492	2.6376
a2	-	1.0246	-	0.8669
a3	0.039	0.3246	2.073	0.1132
a4	-	0.0739	-	0.0253
a5	0.0519	0.0184	0.0286	0.0035
a6	-	0.0039	-	0.0006
a7	0.0251	0.0008	0.0008	0.0001
a8	-	0.0002	-	0.0000
a9	0.0007	0.0000	0.0000	0.0000
a10	-	0.0000	-	0.0000
a11	0.0002	0.0000	0.0000	0.0000

The multipoles due to the persistent currents were calculated for horizontal and vertical field cycles with a computer code REM [4], which has been linked to the ROXIE-program[5]. The persistent dipole and sextupole components are presented in Fig. 1. and 2. as a function of the main field of the corrector.

B. *Quench protection*

The simulations in [6] predict peak voltages of about 150 V and hot-spot temperature of 250 K, when the outer coil quenches at nominal current. For the tests on the prototype magnet an extraction resistor of 0.5Ω will be connected in parallel to each magnet to limit the peak temperatures to about 80 K. The expected voltage across the resistor is then about 300 V. The quench velocities will be verified during the cold tests of the prototype. This will allow to determine whether the external resistor is really required.

III. MECHANICAL DESIGN

A. *Coils*

The coils were wound with 7 or 9 rectangular superconducting wires pre-assembled as flat cables, which facilitates the winding process as compared to the single

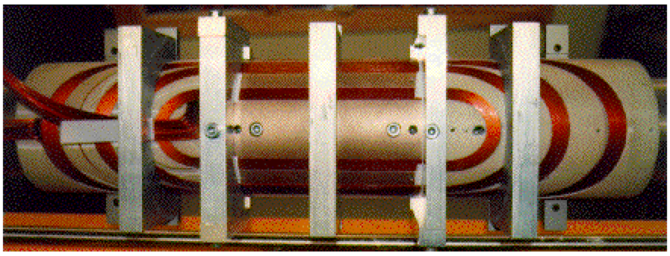

Fig. 3 Inner coil winding. Note the cross-over conductors in the lead end.

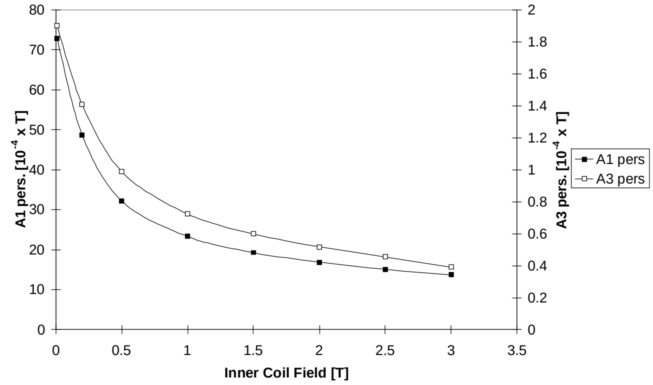

Fig. 1 Dipole and Sextupole component due to persistent currents in the inner coil.

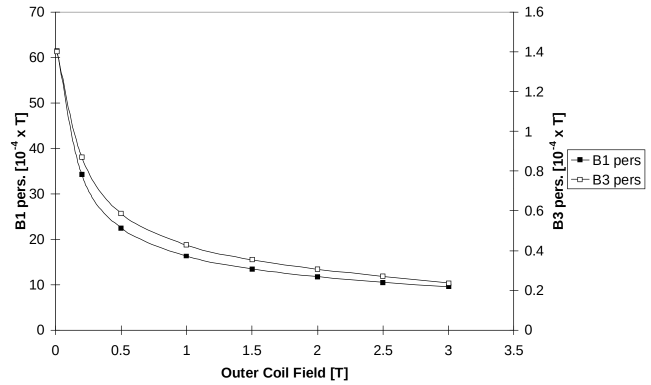

Fig. 2 Dipole and Sextupole component due to persistent currents in the outer coil.

wire technique, where so-called joggles have to be fitted in the ends. The flat cable was made by wetting the with epoxy and spooled on a drum within a precise groove. An intermediate strip with releasing agent was used to separate the turns during curing. Lap-joint tests were carried out to measure the bonding strength, which ranged from 20 MPa at RT to 40 MPa at 77K. The dimensional tolerances of the cross-section of the finished flat cable were within ±0.01 mm over the length of about 50 m. The individual conductors are connected in series in the connection end.

The coils contain CNC-machined fiber-glass end-spacers, and the spacers in the straight sections including the central islands were machined of copper alloy (DIN 1705). The inner coil is shown in Fig. 3. The tooling represents a significant cost in the end-spacer manufacture. This makes the first set about three times more expensive than the subsequent ones. The moulding technique was also successfully tried out using CNC-machined pieces as a model to make the mould. All the voids and empty regions were filled with loaded epoxy before the individual coils were vacuum impregnated and cured at 120 C.

B. *Assembly procedure*

The main parts of the MCBX-prototype are shown in Fig. 4. The inner coils were assembled on a collapsible mandrel and wrapped with a 2 mm thick layer of dry fiber-glass cloth. The inner coil assembly was impregnated and cured prior to assembling the outer coils around it. The two

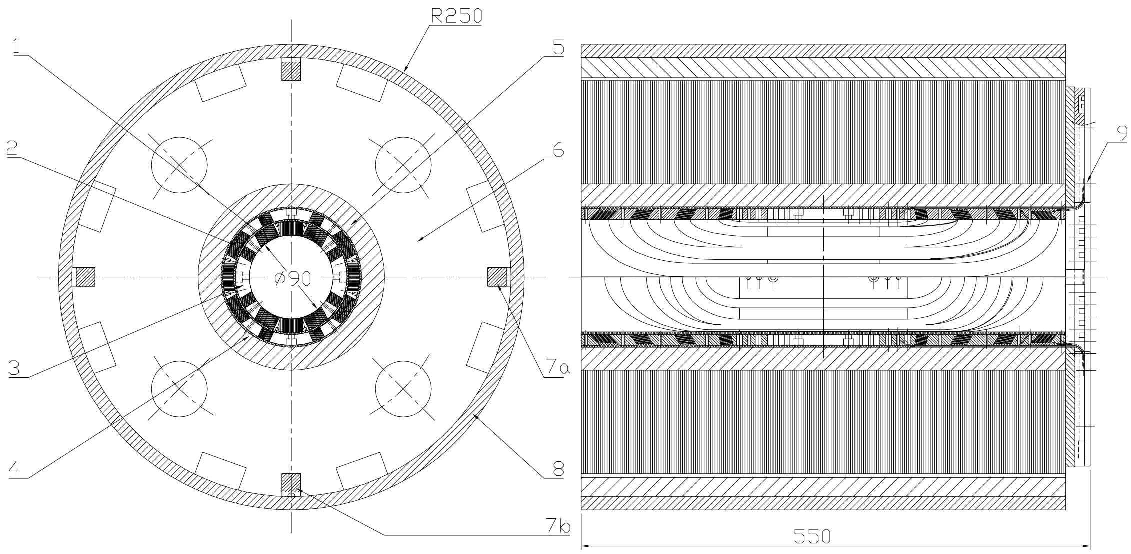

Fig. 4 Cross-section of the MCBX-magnet. 1. Inner Coil, 2. Outer Coil, 3. Bronze coil spacer, 4. Fiber-glass insulation, 5. Al. shrink ring, 6. Iron (Fe37) Yoke laminations, 7a. Vertical, and 7b. Horizontal blocking keys, 8. St. Steel outer shell, 9. End plate for series connections (G10).

magnets were aligned to each other by means of dowel pins in the head spacers and wrapped with fiber-glass. After curing the completed assembly the outermost fiber-glass bandage was turned to a precise dimension. The collapsible mandrel was extracted and the aluminium shrink rings were fitted on. The radial interference of 0.075 mm resulted in 20-25 MPa circumferential stress in the coils. The shrunk assembly showed some elliptic deformation and therefore the ID of the yoke laminations was made 0.4 mm larger. These 2 mm thick Fe37 plates were stacked around the coil assembly, the blocking keys (20 x 20 mm) were mounted, and a 15 mm thick stainless steel cylinder was shrink-fitted around the yoke with a radial interference of 0.23 mm. Each lamination is designed to support the coils radially in one azimuthal direction only [7]. This is made by off-centring the hole in the lamination by 1 mm with respect to the outer boundary. By sequentially stacking four laminations at angular orientations of 0, 90, 180, 270 degrees respectively the coils can be effectively supported and centred. The laminations move inwards during the cooldown and the blocking keys stop the movement at a pre-defined temperature building-up a circumferential stress in the stainless steel outer shell.

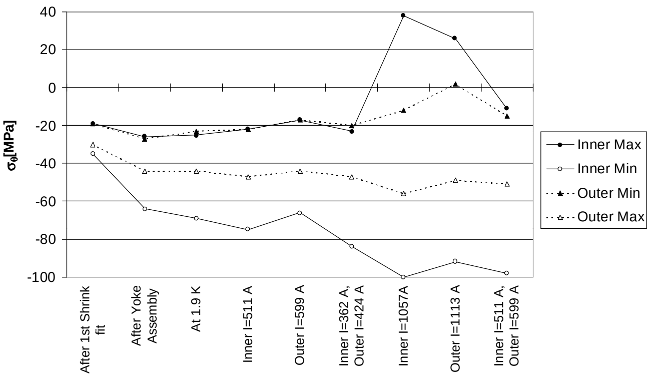

Fig. 5. Evolution of minimum and maximum azimuthal coil stresses at RT, after cooldown, and magnet energised.

Finally, the soldered series connections were made radially on the G10 end-plate. Wires were brought together under pressure and soldered within a groove on a pre-tinned Cu-bar. A conservative overlap of 100 mm per joint was chosen to minimise the heat load.

C. *FE-Analysis*

The assembly parameters were studied with an FE-model in ANSYS® [8]. The interferences were introduced using gap elements between the coil assembly and the aluminium cylinder, between the aluminium cylinder and the yoke, and between the yoke and the outer shell. Friction was not taken into account. The interference between the outer shrink ring and the yoke lamination was simulated by defining initial gap conditions along this boundary as a function of the angular position of the gap element. One horizontal lamination and one lamination acting in vertical direction were modelled. Their "counter-laminations" with a movement in opposite direction were simulated by coupling the nodes on the outer radius of the aluminium cylinder and on the inner radius of the outer shell respectively over their diagonals. The design variables consisted of the interference between the coils and the inner shrink ring, the offset of the hole and the OD of the yoke laminations, and the play in the blocking keys at RT.

The evolution of the azimuthal coil stress for 8 load steps is illustrated in Fig. 5. The clamping system is designed to sustain the magnetic forces at nominal field. It is not rigid enough to resist the deformations at excitation levels close to the short-sample current, where the forces are four times higher. In this case the elliptic deformation of the inner coil, in particular, would result in locally high tensile and compressive stresses and would thereby risk to damage the coils. It is therefore not advisable to train the magnets to their critical current.

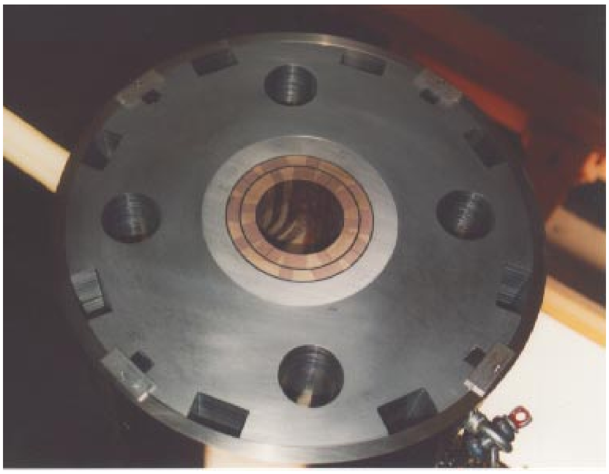

Fig. 6 Mechanical model assembly

D. Mechanical model

A 250 mm long mechanical model shown in Fig. 6. was made to verify the assembly procedure. The test windings of one inner and one outer coil were cut in two and assembled as a half magnet. The diameters were measured before and after fitting the inner and outer shrink rings. This information was then fed back to the FE-model to tune the input data before studying the assembly parameters for the prototype magnet. The measured values agreed very well with the calculations at RT, but the measured thermal contraction factor of the coil assembly was somewhat greater, probably due to higher epoxy content of the coils.

E. Resin system

The resin system used for impregnating the test windings was Ciba-Ceigy: Araldite-F (100 pbw) with HY906 (100 pbw), DY040 (5pbw) and DY073 (0.3 pbw). The hardener HY906, however is known to suffer [9] from brittleness at cryogenic temperatures and therefore HY917 was chosen for the final coils. The flexibilizer (DY040) increases the gas production (1.5 ml/g/1 MGy) when subjected to radiation. Together with different freezing point this has an adverse effect on the low-temperature properties and hence the final coils were impregnated without DY040.

F. Prototype magnet

The prototype magnet has been completed and the cold tests including the magnetic measurements will start at CERN. Although the same radial interference was used for fitting the inner shrink rings of the mechanical model and the prototype magnet, the measured values for the obtained pre-stress were different, the effective interference in the prototype being 0.05 mm smaller than expected. The conductors are enamelled with 0.06 mm thick PVA-layer, which limits the curing temperature to 120 C. The Al-rings were heated up to 160 C, which could have softened the epoxy of the coil assembly and even caused it to flow from the higher compressed regions. This could explain that also the elliptic deformation of the Al-rings was smaller than in the mechanical model, where the curing temperature of the coils was 150 C.

During the winding of the outer coil, in particular, the windings had a tendency to bend radially outward in the position, where the end bend starts. This was caused by a slightly too upright angle of the end turns. An extra allowance of 0.1 mm was machined on the inner faces of the end spacers to ease the winding.

IV. CONCLUSIONS

The first prototype of MCBX corrector with combined horizontal and vertical dipoles has been successfully designed and built in view of fitting it in the very limited space in the LHC inner triplets. The magnetic optimisation was carried out and the optimised coil geometry was imported to CAD- and CAM-programs. The end spacers were CNC-machined from this data. Pre-assembling the conductors as a flat cable made the winding process easier. The iron yoke with the stainless steel outer shell were designed to centre the coil assembly and to sustain the electromagnetic forces in the coils. The measurements on the mechanical model were essential for the optimisation of the assembly parameters of the prototype magnet. The cold tests will give valuable information about the persistent current effects with combined fields. The quench propagation speed will be measured to determine whether the magnet has to be protected with an external resistor.

V. ACKNOWLEDGMENTS

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