Inner Triplet Corrector Package MQSXA for the LHC

M. Karppinen, J. C. Perez, and R. Senis

***Abstract*—The eight Inner Triplets of the LHC will each house a combined corrector magnet assembly, MQSXA, which comprises a skew quadrupole (MQSX) in line with nested skew octupole (MCOSX), octupole (MCOX), and skew sextupole (MCSSX) windings. These superconducting single-aperture magnet assemblies have a bore of 70 mm diameter, and the complete MQSXA assemblies are 530 mm long, have an outer diameter of 180 mm and an approximate mass of 90 kg. In the Inner Triplets the MQSXA assemblies are flanged to the end plate of the high gradient quadrupoles (MQX).**

This paper presents the main design features of the MQSXA and the experience gained with the prototype of the nested part of this magnet assembly, which has been built at CERN. The results of the training tests at 4.3 K and 1.9 K together with the cold magnetic measurements are given.

***Index Terms*—Corrector, superconducting magnet.**

I. Introduction

THE INNER Triplets of the LHC will be equipped with a total of 8 combined corrector magnet assemblies MQSXA, the main parameters of which are given in Table I. They feature a skew quadrupole (MQSX) in line with three nested windings: an inner skew octupole (MCOSX), an octupole (MCOX), and an outer skew sextupole (MCSSX). All four windings which are individually powered are assembled together in the same 530 mm long mechanical structure with an outer diameter of 180 mm, a bore of 70 mm diameter, and an approximate mass of 90 kg.

II. Design and Construction Features

A. Magnetic Design

As seen from the interaction point (IP) the MQSXA assembly is located on the IP side of the high gradient quadrupole MQXA [1] of Q3, to correct for the field errors and the roll of the low-β quadrupoles. The MQSX, the strongest element of the assembly, is designed to produce a gradient of 80 T/m at 550 A. The field strengths of the three nested windings MCOSX, MCOX, and MCSSX at the nominal current of 100 A are 9670 T/m^3, 9220 T/m^3, and 59 T/m^2, respectively.

B. Mechanical Design

The MQSXA magnet assembly is shown in Fig. 1 and consists of a skew quadrupole winding, a package of three nested winding layers (skew octupole, octupole, and skew sextupole), a laminated iron yoke, a stainless steel outer shell, and end plates which house the electrical connections. The quadrupole coils are made by counter-winding two superconducting wires, pre-assembled as a flat cable, around a fiberglass epoxy central post.

TABLE I
Main Parameters of Inner Triplet Corrector Package MQSXA

	MQSX	MCOSX	MCOX	MCSSX	
MAGNETIC					
Nominal field (r=17mm)	1.36	0.0475	0.0453	0.1089	T
Magnetic length	0.223	0.138	0.137	0.132	m
Peak field in coil	3.94	1.34	1.37	1.32	T
GEOMETRIC					
Overall length	530				mm
Coil length	250	150	150	150	mm
Coil inner diameter	70.4	70.4	75.32	80.24	mm
Coil outer diameter	80.4	73.32	78.24	83.16	mm
Yoke inner diameter	85.16				mm
Yoke outer diameter	160				mm
Weight	90 kg				
ELECTRICAL					
Nominal current	550	100	100	100	A
Turns/coil	96	48	52	72	
Stored energy	2116	16	22	39	J
Self inductance	14.0	3.2	4.4	7.8	mH
CONDUCTOR					
Section (H x W)	1.25 x 0.73	0.73 x 0.38			mm
Metal section (H x W)	1.13 x 0.61	0.67 x 0.32			mm
Cu/Sc ratio	1.7	4			
Filament diameter	7	7			µm
Margin to quench	41	63	62	61	%

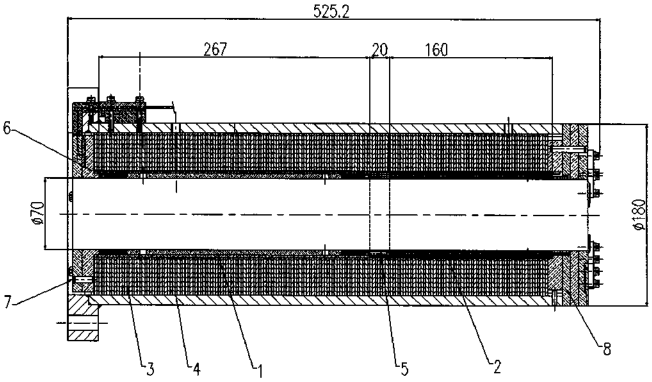


Fig. 1. Longitudinal section of the MQSXA assembly: (1) skew quadrupole winding (MQSX), (2) skew octupole (MCOSX), octupole (MCOX), and skew sextupole (MCSSX) windings (see also Fig. 2), (3) Yoke laminations, (4) stainless steel outer shell, (5) EP GC3 spacer, (6) MQSX connection plate, (7) alignment pin, (8) connection plates of the nested windings.

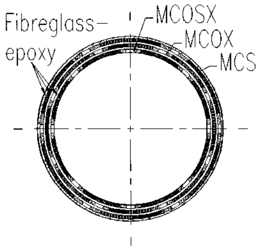
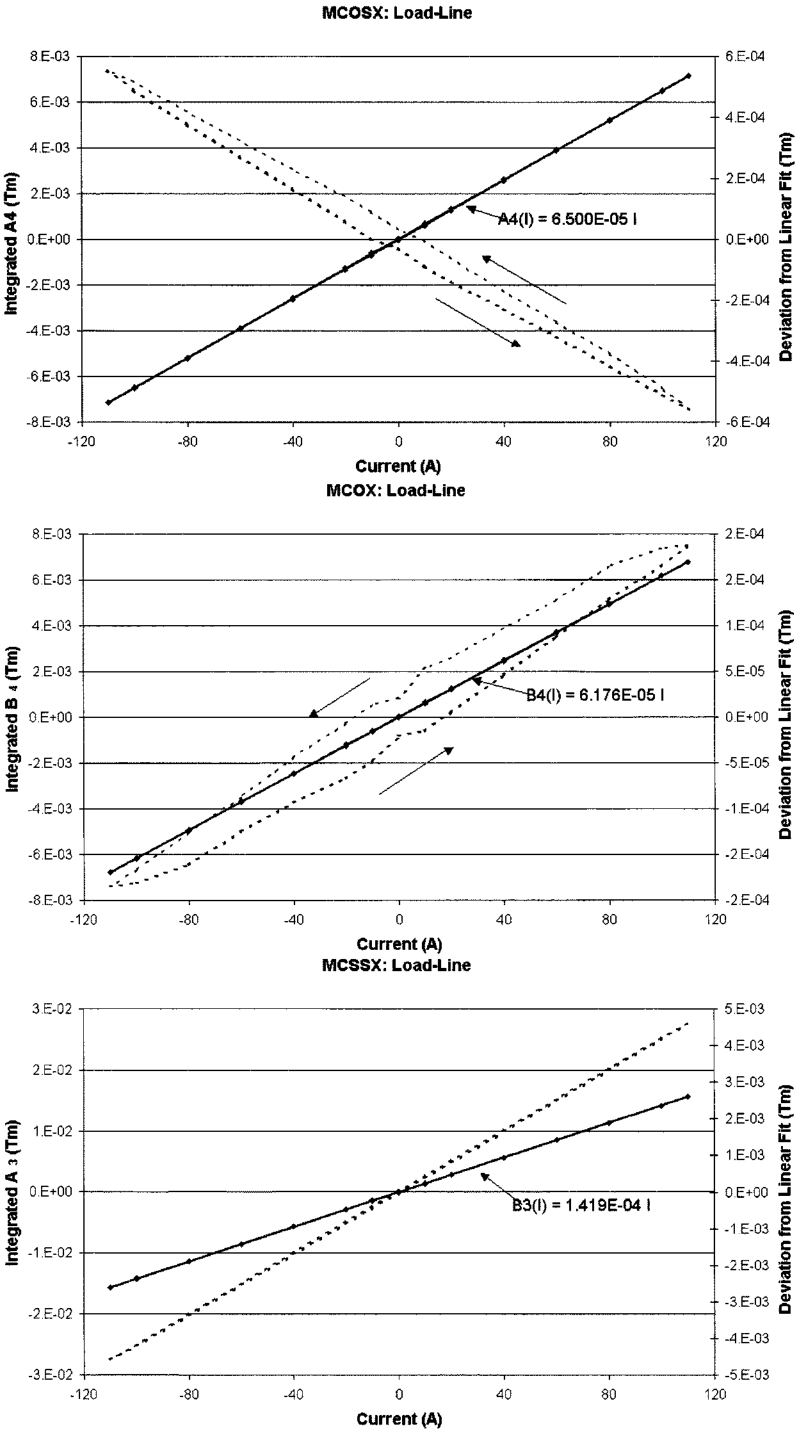


Fig. 2. Cross-section of the coil assembly of the prototype magnet.

Manuscript received September 24, 2001.

The authors are with CERN LHC-Division, CERN European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland (e-mail: mikko.karpinen@cern.ch).

Publisher Item Identifier S 1051-8223(02)04094-0.



MCOSX: Load-Line

MCOX: Load-Line

MCSSX: Load-Line

Fig. 3. Transfer functions for individual powering and the deviations from the linear fit in Tm.

The other three types of coils are wound in the same way with a single superconducting wire of a smaller cross-section. All the superconductors have a rectangular cross-section and are enamel insulated. Each coil is impregnated with epoxy.

In order to avoid conductor movements, a pre-compression is applied to the coils by the shrink fitting of a stainless steel outer shell over the eccentric steel laminations (so-called scissor laminations) that make up the yoke. The laminations are sequentially stacked around the coils in 8 different azimuthal orientations. The radial pressure from the outer shell induces the compressive azimuthal stress in the coils that is needed to prevent tensile strain when the magnet is powered. The magnitude of the pre-compression, determined by the interference fit between the stainless steel outer shell and the yoke laminations around the coils, is chosen to produce pre-compression between 35 and 50 MPa in the coils at the operating temperature.

The outer shell also increases the structural rigidity of the magnet. A flange, welded to one extremity of the shell, attaches the MQSXA assembly to the end plate of the MQXA quadrupole.

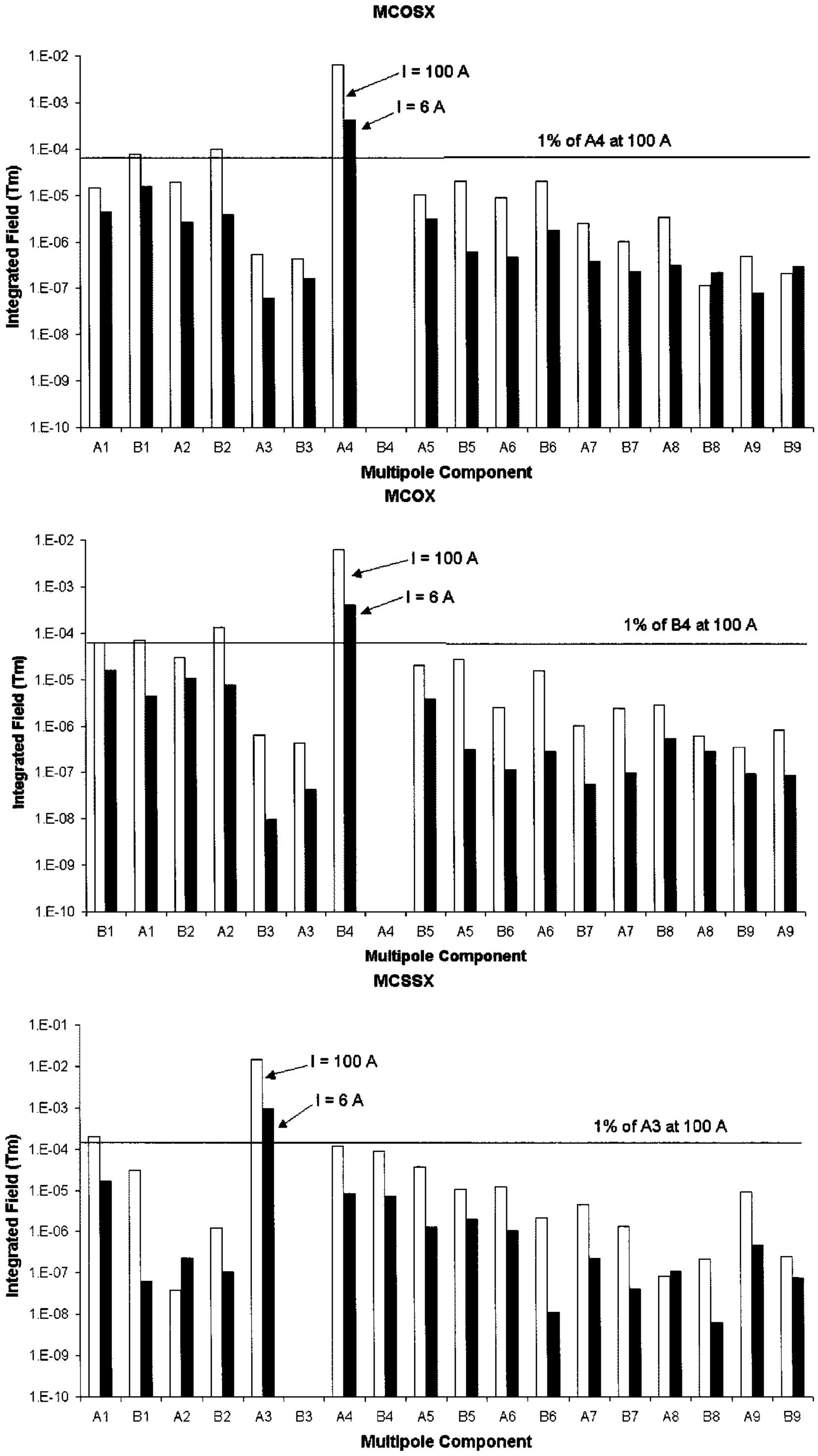


Fig. 4. Measured multipole content at 6 A and at 100 A at 1.9 K for individual powering after feed-down correction.

To keep the ohmic heat load into the helium bath of an acceptable level, the contact resistance of each connection will be less than 3.5 nΩ at 1.9 K. The wires in the flat cable of the quadrupole coil are connected in series by ultrasonic welding after which the connections are soft-soldered onto copper backing pieces for mechanical fastening. The coils of each winding are then connected in series by ultrasonic welding and the connection fastened onto a copper backing piece by soft-soldering.

III. PROTOTYPE MAGNET

To verify the fabrication concept of the series MQSXA assemblies a prototype was built at CERN. The design of the skew quadrupole part being very similar to the MQT tuning quadrupole modules [2] it was decided to limit the prototype to the part consisting of the three nested windings. The cross-section of these nested windings is shown in Fig. 2.

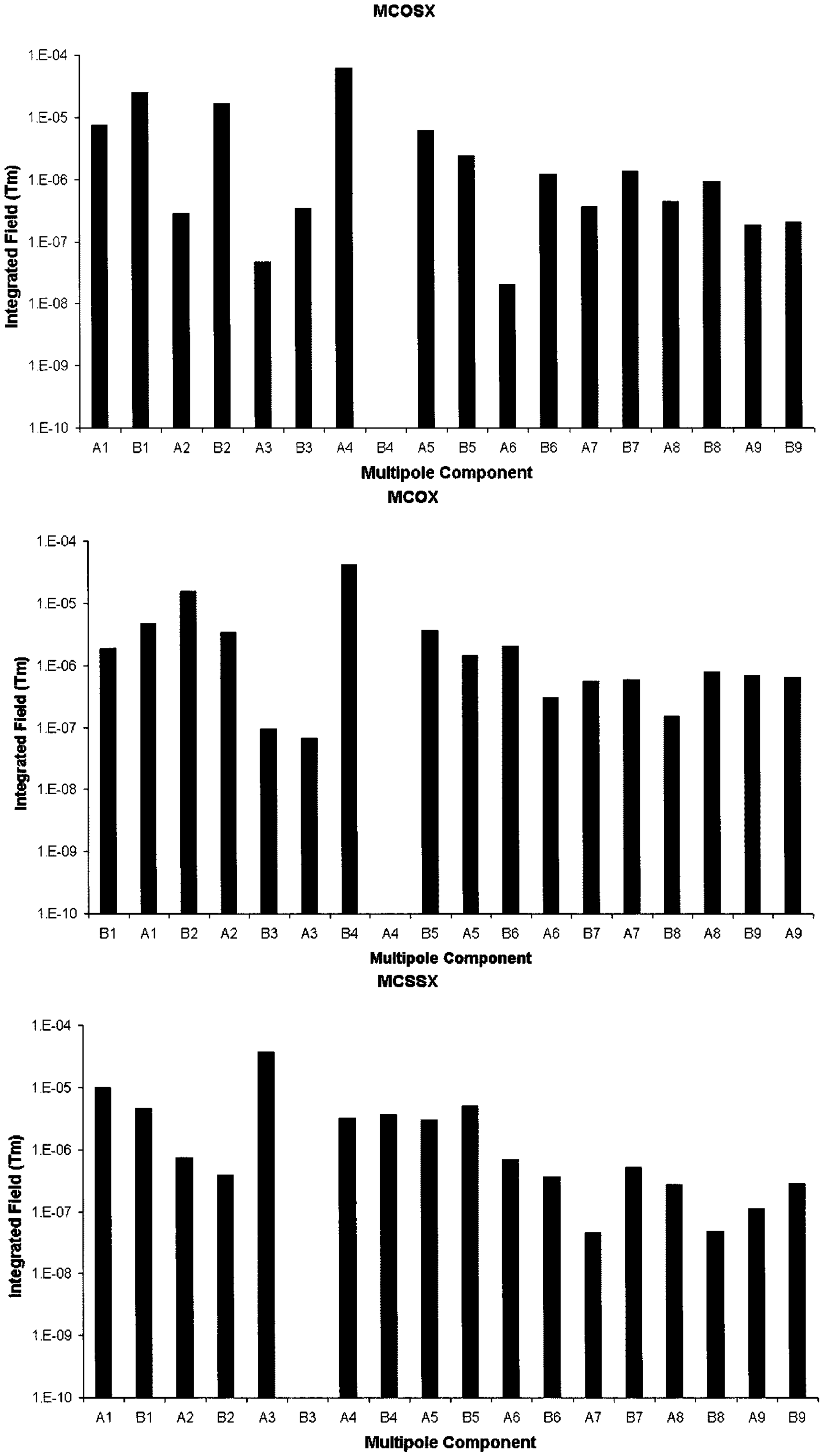


Fig. 5. Hysteresis levels at 0 A at 1.9 K for individual powering.

A. Magnet Assembly

To protect the coils an EP GC3 sheet of 0.2 mm thickness with holes for the dowel pins was first mounted on an assembly mandrel. Then the eight MCOSX coils with a thin layer of resin on the inner face were mounted onto the mandrel and precisely aligned using dowel pins. The coils were then clamped firmly against the mandrel.

The MCOSX coil assembly was surrounded with a fiberglass-epoxy layer using a fiberglass-epoxy pre-preg cloth (SE84/RE292/1000/45%, curing time 1 h at 120 °C, supplied by SP-Systems Ltd.). The glass fraction within the bandage must be increased to approximately 60% by volume forcing excess epoxy out of the bandage by creating a radial pressure on the bandage during the curing. A thermo-retractable film (STTI and Flashtape 2 from Aerovac Systemes, France) wrapped over the coil assembly with 2/3-overlap was used for this purpose.

After curing, the outer diameter of the fiberglass layer was turned to a precise dimension. Then the eight MCOX coils were mounted and precisely aligned around the MCOSX coil assembly and any gaps filled with reinforcing material. The coil assembly was wrapped with another layer of fiberglass-epoxy, which after curing was again turned to a precise diameter. The outermost layer consisting of six MCSSX coils was made in the same way and after curing the outer diameter of the complete coil assembly was turned to create the required interference between the outer shell and the yoke laminations. This radial interference was of (0.12 ± 0.02) mm and corresponds to (30–50) MPa azimuthal compression in the coil at room temperature and also at cold.

The only difference with respect to the series design were that the electrical connections were soft-soldered and the Cu/Sc-ratio of the wire, which was 3.58 instead of 4. Furthermore, the prototype was equipped with monitoring wires to measure the voltage across each coil.

B. Quench Performance

The prototype was first trained and re-trained at 4.3 K at CEDEX in Spain and then the test campaign including training at 1.9 K, cold and warm magnetic measurements was carried out at CERN.

After cooldown to 4.3 K the three winding layers were first powered individually and none of them showed training and no quenches occurred below 200 A.

In the next step the current in two of the layers was set to 100 A or 120 A, while the current in the third layer was ramped up at a ramp-rate of 10 A/s. The lowest current at the moment of quench was 184 A (in the MCSSX), while the current in the other layers was set to 120 A. Finally, when the three layers were connected in series in five different combinations of polarities the lowest quench current was 162 A. After a thermal cycle the individual and series powering tests were repeated and no re-training was observed.

During the third test campaign at the operating temperature of 1.9 K no quenches occurred below 245 A. The hot-spot temperature in the coils was around 50 K and the maximum voltage between 8 and 13 V. The quench did not propagate from one layer to another.

C. Field Quality

The measured transfer functions were within 1% of the theoretical values being 6.500E-5 Tm/A, 6.176E-5 Tm/A, and 1.419E-4 Tm/A for the MCOSX, MCOX, and MCSSX respectively, at the reference radius of 17 mm (see Fig. 3).

The multipole components of each of the three magnets shown in Fig. 4. were below 1% of the main field component, except the B_1 (1.1%) and B_2 (1.5%) of the MCOSX, A_1 (1.1%) and A_2 (2%) of the MCOX, and the B_1 (1.4%) of the MCSSX.

The measured hysteresis of each magnet at zero current is shown in Fig. 5.

During combined powering, especially when ramping the MCSSX with the two other windings set to 100 A, the composite field deviated from the linear superposition of the fields produced by individual powering. This deviation of the skew sextupole component was between 5.8E-5 and 2.5E-4 Tm at the nominal current depending on the powering of the MCOX and the MCOSX. The MCOX had a stronger effect on the MCSSX than the MCOSX. For the multipoles above the 4th order the effect was below 5E-6 Tm. Further analysis is underway.

IV. CONCLUSIONS

The prototype of nested part of the MQSXA, which underwent three thermal cycles, exhibited a very comfortable margin to quench and no re-training was observed. The transfer functions were within 1% of the calculated values and all the multipoles were measured to be less than 2% of the main field. The field produced during combined powering of coils deviates from the sum of the fields with individual powering by a maximum of ∼5.5E-3 Tm for the skew sextupole component, ∼4E-4 Tm, 3.3E-4 Tm respectively for the skew and normal octupole component and less than 5E-6 Tm for other components.

ACKNOWLEDGMENT

The authors want to thank L. Garcia-Tabares and J. Galero for preparing and carrying out the cold tests at CEDEX. They also want to express their gratitude for the whole team of the magnet test station at CERN.

REFERENCES

[1] T. Shintomi *et al.*, “Progress of the LHC Low-b quadrupole magnets at KEK,” *IEEE Trans. Appl. Superconduct.*, vol. 11, no. 1, pp. 1562–1565, 2001.

[2] M. Allitt, A. Hobl, A. Ijspeert, M. Karppinen, D. Krischel, J. Mazet, J. Salminen, and M. Schillo, “Development of superconducting quadrupole corrector (MQT) prototypes for the LHC,” MT-17 conf., Sept. 2001, to be published.