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CM-P00063413

CERN/AT-MA/91-16

LHC Note 161

**DESIGN AND FABRICATION OF THE PROTOTYPE SUPERCONDUCTING TUNING
QUADRUPOLE AND OCTUPOLE CORRECTION WINDING FOR THE LHC PROJECT**

H. Bidaurrezaga, ACICA/CENEMESA, Spain

L. Garcia Tabares, ACICA/INDAR, Spain

R. Perin, N. Siegel

**Presented at the 12th International Conference on Magnet Technology
Leningrad, 23-28 June 1991**

**Geneva, Switzerland
September 1991**

Design and Fabrication of the Prototype Superconducting Tuning Quadrupole and Octupole Correction Winding for the LHC Project

R. Perin, N. Siegel
CERN, Geneva, Switzerland

H. Bidaurrezaga
ACICA/CENEMESA, Spain

L. Garcia Tabares
ACICA/INDAR, Spain

Abstract - CERN is preparing for the construction of the Large Hadron Collider (LHC) to be installed in the LEP tunnel. The magnetic lattice of the LHC will consist of a ring of twin aperture dipoles and quadrupoles, connected electrically in series. To adjust the working point of the machine, so called tuning quadrupoles will be installed in pairs in each regular cell, next to the main quadrupoles. Also, to correct multipolar field errors in the LHC, an octupole correction winding is required near each lattice quadrupole. A nested construction of these two magnets is foreseen.

As part of the LHC R&D programme, CERN and ACICA (a group of five Spanish industries: Abengoa, Canzler, Indar, Cenemesa and AME; since June 1990 Cenemesa is part of ABB, Spain), signed a common development agreement for the design, fabrication and testing of a prototype tuning quadrupole and octupole corrector.

This report describes the design of these magnets, giving details of magnetic and mechanical calculations, including results from existing and specially developed computer codes, and model work. Further, the construction procedures are described, including the facilities and tooling developed by ACICA for this work.

I. INTRODUCTION

The tuning quadrupole and the octupole corrector will be housed in the helium vessel of the main quadrupole and will operate at 2 K [1]. The tuning quadrupoles will allow a tune variation of ± 2 units, and will be used to compensate the tracking differences between the main dipoles and quadrupoles and also the quadrupole error field caused by iron saturation in the dipoles at high field. The operating gradient ranges from - 120 T/m to + 120 T/m. Since the quadrupole error in the main dipole changes sign between the inner and outer beam channels, the two families of tuning quadrupoles of each machine are separately powered by octant such that equal phase advances can be adjusted in the regular lattice of each octant. This results in 25 series connected magnets per power converter.

To save space in the lattice, the octupole corrector, placed near each main quadrupole, is mounted on the vacuum pipe of the tuning quadrupole, where the aperture is sufficient to accommodate it. The coils are of the distributed winding type and their strength ranges from - 10⁵ T/m³ to + 10⁵ T/m³.

The development of these elements has greatly benefited from previous successful solutions reached at CERN and other laboratories, such as the ISR [2], LEP [3, 4], and Fermilab [5] superconducting low-beta quadrupoles, the HERA correction magnets [6] and a CERN model of a

distributed winding [7]. Where possible, the design was oriented towards economic and efficient fabrication methods, in view of a later series production of 800 of these elements needed for LHC.

II. GENERAL DESIGN

The transverse cross-section of the tuning quadrupole with the octupole corrector is shown in Fig. 1 below.

The main parameters of these elements are given in Tables 1 and 2 respectively. The choice of conductor and coil design for the tuning quadrupole is dictated by the need of radial compactness, low excitation current and a reasonable number of turns to wind. The conductor options examined were, multifilamentary, NbTi based, mini Rutherford key-stoned cables and monolithic wires. Two layer coils using the former conductor lead to operating currents of about 3000 A.

Lower currents are favoured to reduce bus-bar cross-section, current lead heat losses and costs of the current supplying system. Further, orderly wound conductors as compared to random winding, goes in the direction of more compact and efficient coils, and hence allows to maintain the outer diameter of the magnet to within 170 mm, leaving 10 mm separation between neighbouring units of a pair, thus avoiding magnetic cross-talk between the two machines. These considerations lead to the choice of a rectangular solid wire and to the comparison of two coil versions: 60 turns and 1600 A

Fig. 1 Cross-section of tuning quadrupole and octupole.

TABLE 1
MAIN PARAMETERS OF TUNING QUADRUPOLE

Maximum gradient	± 120 T/m
Current	± 1600 A
Magnetic length	0.72 m
Peak field in coils	3.8 T
Current density in NbTi at 2 K	1520 A/mm ²
Overall current density in insulated conductor	420 A/mm ²
Inner diameter of coil (warm)	56.3 mm
Outer diameter of coil (warm)	86.5 mm
Inner diameter of magnetic circuit	110.2 mm
Outer diameter of magnetic circuit	170 mm
Length of magnetic circuit	800 mm
Stored energy	12.8 kJ
Self inductance	10 mH

versus 90 turns and 1100 A. The former version was chosen for the prototype, giving a somewhat larger but easier to place conductor, although a lower current version might be considered for the series as a result of system and cost optimization. The wound coils are vacuum impregnated with epoxy resin to ensure mechanical stability and after assembly, compressed by shrink fitted aluminium alloy cylinders, following in this respect the technology of the ISR and LEP quadrupoles. This ensemble is surrounded by the yoke, made of a soft iron tube.

The main field component in the aperture comes from the tuning quadrupole. The forces induced in the octupole coils are therefore directed tangentially or radially inwards and outwards and change sign when the polarity of one magnet is reversed. Mechanical support is required both inside and outside, to provide sufficient compression to resist shear stresses. To minimize space and excitation requirements for the octupole, the coils are wound on the machine vacuum pipe. To resist buckling, a thicker walled tube than in the rest of the machine is required. A toothed tube is foreseen, which serves as winding mandrel and mould and ensures accurate relative positioning of the coils. This component will be obtained by machining for the prototype, but could advantageously be cold drawn for a larger series.

III. THE PROTOTYPE TUNING QUADRUPOLE

A. Conductor

The selected conductor, type F-636-1.9, manufactured by Vacuumschmelze, Hanau, has bare dimensions of 1.35 mm x 2.3 mm, contains 636 NbTi filaments of 46 μ m diameter embedded in a Cu matrix and has a Cu to s.c. ratio of 1.9. Two lengths of about 1100 m each, were made, fabricated as round wire first and then overdrawn to a rectangular shape by rollers to close tolerances (few μ m). The first conductor was overdrawn insulated with 0.06 mm thick coat of polyesterimide enamel, wrapped subsequently with a buttlapped 0.025 mm thick polyimide film bonded with 0.015 mm of glue, resulting in a total insulation

thickness of 0.1 mm. Low adherence of the acryl based glue, made the polyimide layer prone to damage. The second conductor, fabricated bare, was insulated by ISOLA, Breitenbach, with a 0.020 mm thick polyimide film, coated with a 0.005 mm layer of esterimide based glue and applied 2/3 overlapped. This insulation presents adequate flexibility to adapt itself to the conductor bending radius at the coil ends. The specified and measured critical currents at 4.2 K are shown in Fig. 2 below. The specified values were derived reducing slightly (8%), the average results obtained with the LEP low-beta quadrupole conductor, which exhibited an anisotropy of about 20% at 5 T. For the present fabrication the anisotropy measured at 5 T is about 8%.

B. Coil design

The coil is made in 10 layers of 6 turns each, subdivided in two blocks to minimize the 12 and 20 pole field error components. Higher order multipoles are negligible. The coil geometry, optimized by analytic calculations with a programme developed for this application is shown in Fig. 3 below.

The relative integrated field errors, calculated for the ideal coil geometry and assuming a relative permeability of the central post of 1.01, are 0.15×10^{-4} for the 12 pole ($r = 10$ mm), and below 0.1×10^{-4} for the higher order terms. The coil ends are shaped for a nearly equal perimeter condition to facilitate coil winding and the layers are spaced axially such as not to exceed in this region the peak field of the two dimensional section, which is 3.8 T. The coils are wound around central posts made of stainless steel of type 316LN. These posts are machined out of a centrifugally cast tube with a NC and programmable machine tool. The block separation spacer and the end spacers are made from Cu alloy. The wedged shaped spacers of the ISR and LEP quadrupole coils placed on the median symmetry planes, which were machined after glueing them onto the coils, are suppressed. This requires precise moulding to ensure simultaneously conductor positioning (for field quality) and coil compactness (for required prestress). Glass epoxy shims are inserted in the

Fig. 2 Load line of tuning quadrupole and critical currents.

DIMENSIONS OF CONDUCTOR

Fig. 3 Coil cross-section of tuning quadrupole.

blocks to compensate for conductor tolerances and resin shrinkage. A set of light clamping tools for winding and of heavy clamping tools for pressing into shape and for the impregnation are foreseen. Coil potting is done with a bisphenol A resin cured at 120 °C with a specially formulated anhydride hardener and accelerators supplied by CIBA-Geigy, Basel.

C. Coil clamping structure

The finished coils are provisionally clamped and assembled with regularly spaced glass epoxy bandings, which are machined to a precise diameter, and then surrounded by a stainless steel sheet, inserted as antifriction layer between the coils and the aluminium cylinders. The sheet has longitudinal grooves machined into it to allow the penetration of the superfluid helium to the outside of the coil. The shrink fitted, 8 mm thick aluminium cylinders, made for a nominal interference of about 0.11 mm on the outer coil diameter, will provide a minimum coil prestress of 2.6 daN/mm² at 2 K. The maximum tensile stress induced by the magnetic forces at full field, calculated analytically and checked by ANSYS [8], is 2.2 daN/mm². Considering the differential thermal contractions and the machining and material tolerances in the structure and in the coil, a maximum compression of 4 daN/mm² may be reached at room temperature in the assembled coils, which should however still be safely resisted by the insulation.

D. Yoke

The yoke, made of a soft iron tube, is linked to the coil assembly by four sets of precision pins, each set consisting of two pairs orthogonally placed along the 45 degrees symmetry planes, ensuring thus coaxial positioning of the coil assembly inside the yoke tube. The pins fit tightly in the aluminium cylinders but can slide radially and longitudinally in the yoke to allow for differential thermal contractions. They must resist the weight and radial forces of about 500 daN/mm arising from a coil/yoke offcentering.

E. Expected performances

The contribution of the yoke to the central gradient is about 14.5%. The attenuation of the gradient due to iron saturation at nominal current according to calculations with the POISSON code is 0.11%. The margin from operational to critical current along the load line is 27% for the specified critical current and 40% for the measured conductor performance scaled to 2 K. The maximum quench voltage and temperature assuming $I = 1600$ A, no energy extraction, and only the small block of one coil becoming normal are 70 V and 83 K. If the eddy currents in the aluminium cylinders are taken into account, these values decrease by about 10% [9]. Although these values appear safe, a quench detection system and antiparallel connected protection diodes across the magnet terminals should be considered for the LHC to facilitate run-down and avoid quench propagation. During ramping, at a rate of 1600 A/min, the eddy currents flowing in the aluminium cylinders will decrease the gradient by an equivalent of -0.14 A, corresponding at injection to a reduction of the quadrupole strength of $dK = -7 \times 10^{-6}$ and to a tune shift of -0.01. This effect will be enhanced mainly by the solid yoke and will have to be corrected by proper current adjustment. For the series quadrupoles, the filament diameter shall be about 15 μ m, to reduce ramping losses and the effects of persistent currents.

F. Short model of the structure with simulated coils

A 15 cm long model has been made to test the described assembly. The coils are replaced by stainless steel and glass epoxy sectors to achieve a structure with an overall Young's modulus similar to the real coils. Tests at room temperature have shown that the tolerances, prestress and assembly procedure can be achieved. Tests at cryogenic temperature are in progress.

IV. THE PROTOTYPE OCTUPOLE CORRECTOR

The following geometrical constraints are imposed:

- inner vacuum pipe diameter of 43 mm [1],
- outer diameter of banding 52.4 mm, leaving 2 mm radial gap between octupole and tuning quadrupole for the circulation of superfluid helium.

The thickness of the vacuum pipe, coil and banding results from a choice of materials and a compromise of margins to buckling resistance of the pipe, allowable shear stresses, and of operational margin of the winding. The pipe is made from stainless 316LN, ensuring low permeability and high strength and the banding from high strength aluminium alloy. The selected conductor has a bare diameter of 0.5 mm, with a Cu to s.c. ratio of 2. It is then varnish insulated to a diameter of 0.54 mm followed by a glass fibre wrapping preimpregnated with a B-stage epoxy to a final diameter of 0.62 mm. The coils are wound on the insulated vacuum pipe on an average diameter of 48.4 mm and have 10 turns per pole. They are covered by a glass-epoxy prepreg, baked to polymerize the impregnation resin and banded by rectangularly shaped

TABLE 2
MAIN PARAMETERS OF OCTUPOLE CORRECTOR

Maximum strength (B'')	10^5 T/m^3
Current	216 A
Magnetic length	0.72 m
Peak field in winding	3.1 T
Current density in NbTi at 2 K	3300 A/mm^2
Inner diameter of vacuum pipe	43 mm
Minimum wall thickness of pipe	2.3 mm
Average diameter of winding	48.4 mm
Outer diameter of aluminium banding	52.4 mm
Thickness of banding	1.4 mm
Self inductance	0.6 mH

aluminium wire applied under tension. The coil sustains a sector of 15° , which suppresses the 24 pole field component. Turns of adjacent poles are wound in the ends as a single 20 turn coil, resulting in a total of 4 coils per octupole, thus simplifying winding and connections. Neglecting the octupole field, the forces acting on the coils due to the quadrupole field have an equal absolute value of 1260 daN/m (per 20 conductors) and are directed as shown in Fig. 4.

For a prestress in the banding of 17.5 daN/mm^2 at 2 K, the radial pressure applied on the coil is 1 daN/mm^2 and the safety factor on the collapsing pressure of the pipe is 2.3, whereas the safety margin on the pressure required to resist the shear stresses is 20%. The latter pressure is calculated assuming a friction coefficient of 0.25, which for safety was reduced by about a factor 1.5 from those quoted in the literature [10]. Although the octupole coil may be limited by shear stress, the preference was for an increased safety against failure by buckling. The ratio of banding pressure to outward pressure due to coil forces, results in a safe factor of 10. From critical current performance of commercially available wire, scaled to 2 K, the operating margin along the load line is 27%.

Fig. 4 Forces in octupole windings due to quadrupole field.

V. PRESENT STATE

All the tooling required for the fabrication of the tuning quadrupole and octupole corrector have been designed by ACICA and built in Spain following ACICA's specifications. The winding machine, based on a rotating mandrel and incorporating a novel swivelling device, the brake and the cable tensioning device are all operational. The tooling for winding, pressing and impregnating the coils is delivered, as well as all the coil components. Coil winding should start in July 1991 and the first prototypes are planned for the first half of 1992.

ACKNOWLEDGEMENTS

Thanks are due to the members of the Magnet Group who have contributed to this work, especially to D. Regin and S. Pichler for their advice concerning the tuning quadrupoles, H. Depierre for installing instrumentation at ACICA, and D. Cornuet for his advice concerning the octupole corrector. It is a pleasure to acknowledge the fruitful and continuing collaboration with the personnel of ACICA, in particular: J.R. Barturen, Cenemesa (at present in ABB/Spain) for design work, J. Etcheandia, INDAR, for the development of tooling, model and fabrication procedures and J.M. Cubert, INDAR, and M.A. Rodriguez Borra, SERCOBE, for their continuing support. Our sincere thanks also to Mrs C.L. Jullien for the perfect typing work and to A. Russo for preparing the figures.

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