EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN LEP-MA/89-68

THE BENDING MAGNET SYSTEM OF LEP

by

M. Giesch and J.P. Gourber

Presented at 11th International Conference on Magnet Technology,
Tsukuba, Japan, 28 August - 1 September 1989

Geneva, Switzerland

August 1989

THE BENDING MAGNET SYSTEM OF LEP

M. Giesch and J.P. Gourber, CERN, Geneva, Switzerland

ABSTRACT

The main bending magnets of LEP are made of 3280 "steel-concrete" cores of 5.75 m length, disposed end-to-end generally in long units of six cores. Just prior to transportation into the tunnel, the cores are pre-assembled at the surface in pairs equipped with their four water-cooled aluminium bars and with their vacuum chamber. The bars are welded together in the tunnel by the MIG process so as to form a single powering circuit equivalent to one turn on each pole. Water-cooled cables are used to interconnect the bending magnets between the arcs. The paper recalls the main features of the cores and describes the excitation circuit in more detail; the criteria retained for the design of the bars and cables are presented together with the experience gained with the series production and with the assembly and interconnection of the magnets.

INTRODUCTION

The large electron positron collider (LEP) which is now being commissioned at CERN has a large circumference and a correspondingly low bending field (215 G at 20 GeV and only 1100 G at the maximum energy of 100 GeV) in order to limit the synchrotron radiation. This feature and the overall economical constraints have led to a specific design of the bending magnets based on the use of steel concrete cores excited by long excitation bars⁽¹⁾.

The regular cells in the arcs are 79 m long and comprise each two bending magnet units of six cores (Fig. 1) and two quadrupoles independently powered. At the ends of the arcs there are shorter cells with units of 4 or 2 cores. In order to reduce the synchrotron radiation at the experiments, the last half cell at each arc end incorporates a one tenth field magnet of 23.4 m length also connected in series with the main bending magnets.

THE STEEL CONCRETE CORES

The design, manufacture and performance of the steel-concrete cores have been described in other papers⁽²⁾⁽³⁾⁽⁴⁾ and are only briefly recalled here. The 3280 cores of 5.75 m long and 4.6 t mass are made of stacks of low-carbon steel laminations, 1.5 mm thick, spaced by 4 mm and embedded in a cement mortar. Four longitudinal rods compress the core which behaves like a prestressed concrete beam (Fig. 2). This construction with a steel filling factor of only 0.27 results in a large saving with respect to a classical all steel magnet; furthermore, the field enhancement in the steel laminations is favourable for the magnetic performance of the magnet specially at injection level. The cores have been produced by two civil engineering firms over a period of 3 years. Upon delivery at CERN, the mechanical strength and the gap geometry have been measured on each individual core; these measurements served for the acceptance of the core and to determine the angular position of the median plane which was later used for the alignment in

FIGURE 3: Excitation circuit of the bending magnets

position by stainless steel supports, which are dimensioned such that free movement of the bars, due to thermal elongation is guaranteed over the entire length of the magnet unit. The bars are fixed to the end-plate of the first core at one end of the magnet unit, movements due to thermal elongation are taken up by means of flexible connections at the other end (Fig. 4). Interconnection of dipoles behind the quadrupoles in the arcs is made by bars of square cross-section which at the same time provide the distribution of the cooling water to the excitation bars. Interconnection between the arcs is made by water-cooled cables.

Aluminium was imposed as conductor material by the demineralized water circuit common with that of the vacuum chamber. Electro-graded aluminium E-Al 99.5 was used throughout.

A cost optimization was done by minimizing the sum of the capital cost and electricity cost for 30000 hours of operation at 70 GeV. It gave an optimal current density around 0.8 A mm^{-2} which led to a cross-section of $44 \times 90 \text{ mm}^2$ with a cooling hole of 11.5 mm for the excitation bars and $60 \times 60 \text{ mm}^2$ with a

cooling hole of 15 mm for the interconnection bars. The excitation current at the maximum energy of 100 GeV is 4480 A and the total voltage 3600 V.

In order to save costs on components and installation, the excitation bars have been manufactured in lengths of about 12 m so as to equip pairs of cores.

The insulation of the bars is made from epoxy preimpregnated glass tape of 0.28 mm thickness. After bending, machining, welding and sandblasting of the bars, 4 layers of tape were applied with a half overlap, giving after curing a nominal insulation thickness of 2 mm. Curing of the insulation was made in an autoclave filled with asphalt compound under a pressure of 7 bar. The curing time was 8 hours at 160°C . Each finished bar passed a high-voltage test at 8 kV r.m.s. for 1 min after a minimum of 6 hours immersion in water. The radiation resistance of the insulation is $5 \cdot 10^7 \text{ Gy}$.

Four water-cooled cables are used to connect the dipoles between the arcs. A cross-section of the cable is shown in Fig. 5; it is made from 6 solid aluminium sectors with a section of 300 mm^2 each, spaced around the central cooling tube. The insulation between the conductor and the outer copper shield is a halogen-free EPR compound of 3.4 mm thickness. The nominal outer diameter is 67 mm, the bending radius about 1.5 m. The cable ends are welded to the excitation bars by means of simple connector pieces.

In order to avoid static pressure problems due to the 45 m shaft depth, conventional aluminium cables have been used for the part of the circuit between the converters at the surface and the tunnel; 12 aluminium cables of 630 mm^2 cooled by natural convection were needed for each branch of the circuit.

ASSEMBLY AND INSTALLATION

Preassembly of the dipole pairs was made in a dedicated surface building at a rate fixed by the installation in the tunnel (3 to 12 pairs of cores per day). The assembly comprises the following operations: alignment of the two cores, mounting of the four excitation bars using an automated frame, mounting of the vacuum chamber, glueing of the switches for thermal protection of the bars, insulation tests of the bars at 7 kV d.c.

FIGURE 4: Interconnection of bending magnet units

- 1 Cooling tube E-Al 99.5 $\varnothing$ 15/18 mm
- 2 Conductor segments
E-Al 99.5 6 x 300 mm²
- 3 Separating tape
- 4 Insulation EPR 3.4 mm
- 5 Copper tape 0.1 mm
- 6 Sheath PE - copolymer 3.1 mm

FIGURE 5: Cross-section of water-cooled cables

Fig. 6 shows the mounting of the inner bars using the automated frame: the lower inner bar being already installed, the upper one is moved towards its final

FIGURE 6: Installation of bars

position. After assembly, the pairs were clamped in special frames and transported by monorail into the tunnel.

There, after alignment of the dipole pairs, the excitation bars were joined by welding. The ends of the bars had been machined such that when placed end to end a V-shaped cavity is formed which was filled with aluminium using the MIG-welding technique. A stainless steel tube of 12 mm inner diameter and 1 mm thickness is embedded in the weld and assures the continuity of the cooling hole

In order to avoid piercing this tube by the arc, it is shrink-fitted with a 3 mm thick aluminium tube which disperses the heat. A water-cooled jig was used for holding the ends in place during welding and to keep the temperature of the insulation, which starts at 100 mm from the end, at a temperature below 100°C. Fig. 7 shows the bars clamped with the junction tube prior to welding. After welding, the junctions are insulated by two U-shaped channels nested together so as to surround completely the bar. These channels are made from a non-hygroscopic polyester compound moulded under high pressure.

FIGURE 7: Welding jig

Interconnection of bending magnet units is made as shown in Fig. 4. The interconnection bars are welded directly to the excitation bars on one end (fixed end) and via flexible connections at the other end (floating end). The bending magnet units have two cooling circuits in parallel, each being constituted of one inner and one outer excitation bar in series. The water connections are made from aluminium tubes welded into holes, machined at the ends of the excitation and interconnection bars. Tubes which are between bars at different electrical potential are equipped with insulators. The end connections are enclosed in glass polyester covers bolted to the core end plates. During the interconnection work in the tunnel, a 30 bar pressure test and a flow test were performed on each half cell; an insulation test was also done at 5 kV d.c. prior to welding the two flexible connections.

The interconnection work in the tunnel lasted about 16 months without major difficulties. The whole circuit of about 90 km of bars showed an insulation resistance of about 1 M Ω .

ACKNOWLEDGMENTS

The successful completion of the project owes much to the know-how of the manufacturing firms. Cockerill-Sambre (B) and Styner & Bienz (CH) supplied the steel laminations; L'Entreprise Industrielle (F) and PORR AG (AU) manufactured the cores; Ansaldo (I) and Kabelmetal (D) supplied the bars and water-cooled cables respectively; Metareg (F) and Entrepouse (F) performed the assembly and installation work.

The authors are also grateful to many colleagues at CERN who participated to this project from the design stage to the final commissioning.

REFERENCES

- (1) Resegotti, L., The LEP magnet system. In *Journal de Physique*, Vol. 45, Colloque C1, 1984, pp. C1-233-39.
- (2) Gourber, J.P., Billan, J., Laeger, H., Perrot, A., and Resegotti, L., On the way to the series production of steel-concrete cores for the LEP dipole magnets. In *IEEE Trans. on Nucl. Sci.*, Vol. NS-30, No. 4, Part. II, 1983, pp. 3614-16.
- (3) Billan, J., Gourber, J.P., Henrichsen, K.N., Laeger, H., and Resegotti, L., Influence of mortar-induced stresses on the magnetic characteristics of the LEP dipole cores. In *IEEE Trans. on Magnetics*, Vol. 24, No. 2, 1988, pp. 843-46.
- (4) Billan, J., Gourber, J.P., Guignard, G., Henrichsen, K.N., Maugain, J.M., and Wolf, R., Magnetic performance of the LEP bending magnets. In *Proc. 1989 Part. Acc. Conf.*, Chicago, March 1989.