EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN ISR-BOM-GE/80-22

THE EIGHT SUPERCONDUCTING QUADRUPOLES FOR THE ISR HIGH-LUMINOSITY INSERTION

by

J. Billan, K.N. Henrichsen, H. Laeger, Ph. Lebrun, R. Perin, S. Pichler, P. Pugin,
L. Resegotti, P. Rohmig, T. Tortschanoff, A. Verdier, L. Walckiers, R. Wolf

Presented at XIth International Conference on High Energy Accelerators,
CERN, Geneva, July 7 - 11, 1980

Geneva, Switzerland
July 1980

THE EIGHT SUPERCONDUCTING QUADRUPOLES FOR THE ISR HIGH-LUMINOSITY INSERTION

J. Billan, K.N. Henrichsen, H. Laeger, Ph. Lebrun, R. Perin, S. Pichler, P. Pugin,
L. Resegotti, P. Rohmig, T. Tortschanoff, A. Verdier, L. Walckiers, R. Wolf

CERN, Geneva, Switzerland

ABSTRACT

Eight superconducting quadrupoles for a high-luminosity insertion in the ISR have been produced by industrial firms according to CERN design and manufacturing specifications, and assembled and tested at CERN. The horizontal cylindrical cryostats, which contain windings and steel yoke in a boiling helium bath, have a 173 mm warm bore. For 31 GeV beam energy, the maximum operating gradient on the quadrupole axis is 43 T m^{-1} and the maximum field in the windings is 5.5 T. Sextupole windings provide a linear variation of the gradient of up to 4 % over the bore width and dodecapole windings trim the field pattern as a function of excitation. This paper reports about production history, acceptance tests, and performance. The results of magnetic measurements are also summarized. The insertion will be installed into the ISR as from August 1980.

1. INTRODUCTION AND DESCRIPTION OF THE QUADRUPOLES

A beam focusing insertion, using classical quadrupoles and known as "steel low-beta insertion"$^{1)}$, has been in operation for several years at intersection 1 of the CERN Intersecting Storage Rings (ISR), where it increases the luminosity by a factor 2.3. A more powerful insertion, which is expected to reduce the effective beam height by about a factor 6 at intersection 8, with a corresponding increase of the luminosity$^{2)}$, will require eight superconducting quadrupoles. The design parameters of the superconducting magnets, which are determined by beam optics requirements, are given in Table 1. In addition to the quadrupole gradient of up to 43 T m^{-1}, the magnetic field must have a substantial sextupole component in order to match the off-momentum particle orbits, because of the positive chromaticity of the ISR working lines. Dodecapole windings are needed to trim the field pattern as a function of the excitation.

Table 1

Parameters of the superconducting magnets for the insertion at 31 GeV/c

Name		SL1/SL2	SL3/SL4	SL5/SL6	SL7/SL8
Quadrupole magnetic length	[m]	0.65	1.15	1.15	0.65
Quadrupole gradient	[T m^{-1}]	40.0	42.9	37.9	37.9
Sextupole magnetic length	[m]	0.74	1.24	1.24	0.74
Sextupole gradient derivative	[T m^{-2}]	20.6	18.7	21.1	21.5

Figure 1 shows two sections of a quadrupole in its cryostat. The warm bore of the cryostat is 173 mm in order to accommodate the normal ISR vacuum chamber and its bake-out equipment. The helium vessel has a cold bore of 204 mm: its inner tube has a 10.5 mm thick wall with milled grooves into which the sextupole and dodecapole windings are located. A wrapping of aluminium alloy wire under strong tension clamps these auxiliary windings by means of epoxy-silica wedges. An annular clearance of about 1 mm is left between this structure and the quadrupole coils, to avoid any internal constraint on the latter: liquid helium has there an unobstructed passage.

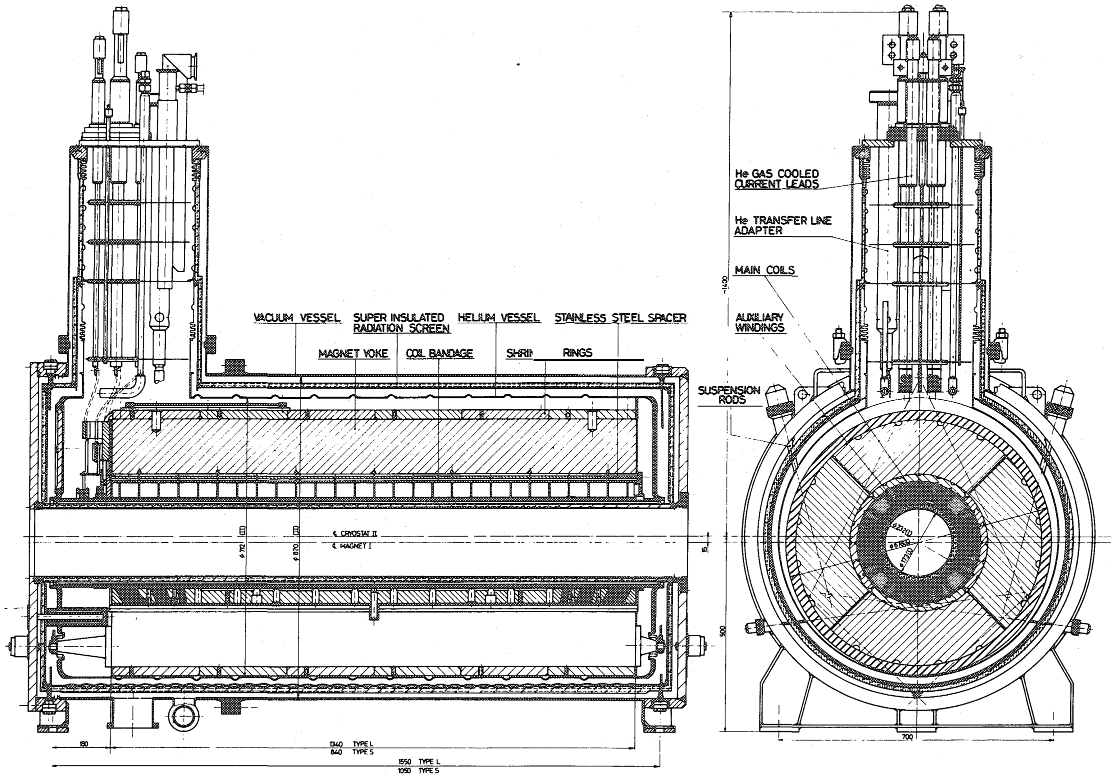

Fig. 1 Longitudinal and transverse sections of a quadrupole in its cryostat

The conductor of the quadrupole coils is a solid composite wire of rectangular cross-section of 1.8 x 3.6 mm^2, containing about 1250 twisted NbTi filaments, 50 μm diameter, inside a copper matrix. It is insulated with enamel and polyimide tape. Each coil, which occupies exactly a 90° cylindrical sector, 38.5 mm thick, has 290 turns, continuously wound in three quasi-rectangular blocks on a central stainless steel post, and spaced by copper wedges of suitable width to approximate a cos 2θ distribution$^{3)}$. The coil ends have a constant perimeter profile, which makes it possible to wind them under strong tension. Each coil is individually moulded and vacuum impregnated with epoxy resin.

The four coils are wrapped together with glass epoxy bands, to form a compact self-supporting cylinder, which is able to withstand the large pre-compression required by mechanical stability in operation$^{4)}$. The annular spaces between the bands constitute cooling channels. They are linked by grooves in the four stainless steel spacers, which maintain the optimum distance between coils and yoke, as defined by the magnetic design$^{3)}$, and also protect the coils from direct contact with the steel yoke quadrants, which have a considerably different thermal contraction. Both the yoke quadrants and the spacers are separated from each other by 2 mm wide gaps, so that they may move concentrically and follow the coils in their radial contraction. The yoke is surrounded by shrink-fitted aluminium alloy rings which apply the necessary precompression to the coil package via the yoke quadrants and the spacers, after cooldown. Thanks to this large azimuthal prestress, no tensile stress appears inside the coils under the action of the electromagnetic forces and the magnet can perform satisfactorily up to near the critical current. The excitation characteristic of the quadrupoles is shown in Fig. 2.

2. PRODUCTION AND TESTING

After the successful construction and test of a prototype at CERN[5,6], the production of the eight quadrupoles was entrusted to industrial firms, selected by competitive tendering. Only the auxiliary windings were wound by CERN technicians. Vacuumschmelze, Hanau, supplied the superconducting wire; Isolawerke, Breitenbach, insulated it, Alsthom-Atlantique, Belfort, produced the quadrupoles proper and Leybold-Heraeus, Cologne, the cryostats. Extensive tests were performed by CERN to ascertain that specifications were met and acceptance criteria fulfilled.

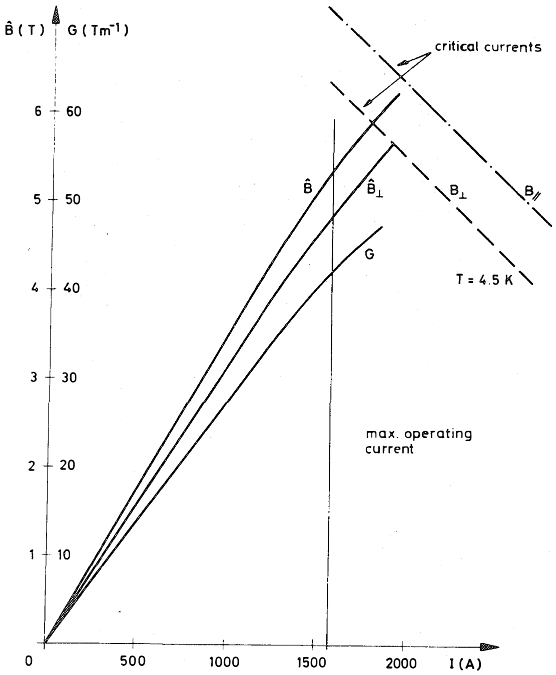

Fig. 2 Load lines and critical currents at 4.5 K

The internal structure of the composite wire was examined and its mechanical and electrical properties, in particular the critical currents for field parallel and perpendicular to the broad face (Fig. 2), were measured on two wire samples per spool. The surface quality was continuously inspected and the transverse dimensions were recorded at close intervals before and after insulation to prepare for eventual shimming of the coil spacers.

Magnet manufacturing was based on the methods and techniques which had been developed in the construction of the prototype[5,6]. The necessary check on interturn and ground insulation was provided by a continuous record of circuit resistances during winding. The tension of the conductor was automatically maintained within the required limits. Close dimensional checks were performed on all components and subassemblies, and applied forces were regularly measured. Alsthom had not to guarantee the magnet performance, but accepted responsibility for correct manufacturing to be demonstrated by the ability of the quadrupole to withstand, without damage, five quenches at 1800 A excitation level. This acceptance test was performed in a vertical cryostat immediately after delivery to CERN and was withstood by all quadrupoles: the number of quenches required to reach this excitation level, which is very near the critical current, varied from a minimum of 6 to a maximum of 18.

The cryostats[7] were assembled around the magnets by Leybold-Heraeus' technicians at CERN. In order to avoid doubtful joints, the cold vessel was entirely welded. As assembly proceeded, the leak-tightness of each enclosure was systematically checked with helium leak detectors, after all vacuum and pressure tests prescribed by the safety rules had been performed. At the end of assembly, overall leak rates were measured and found lower than the specified values of 10^{-9} mbar l s^{-1} for the helium enclosure and 10^{-6} mbar l s^{-1} for the vacuum vessel. Each cryomagnet underwent cryogenic tests before magnetic measurements. The heat intakes corresponded well to the design values of 3 to 3.5 W. Helium consumption at full power is 13 to 14 l h^{-1}, due to current leads, cryostat and transfer line. All eight quadrupoles are now ready for installation. Four of them are shown in Fig. 3.

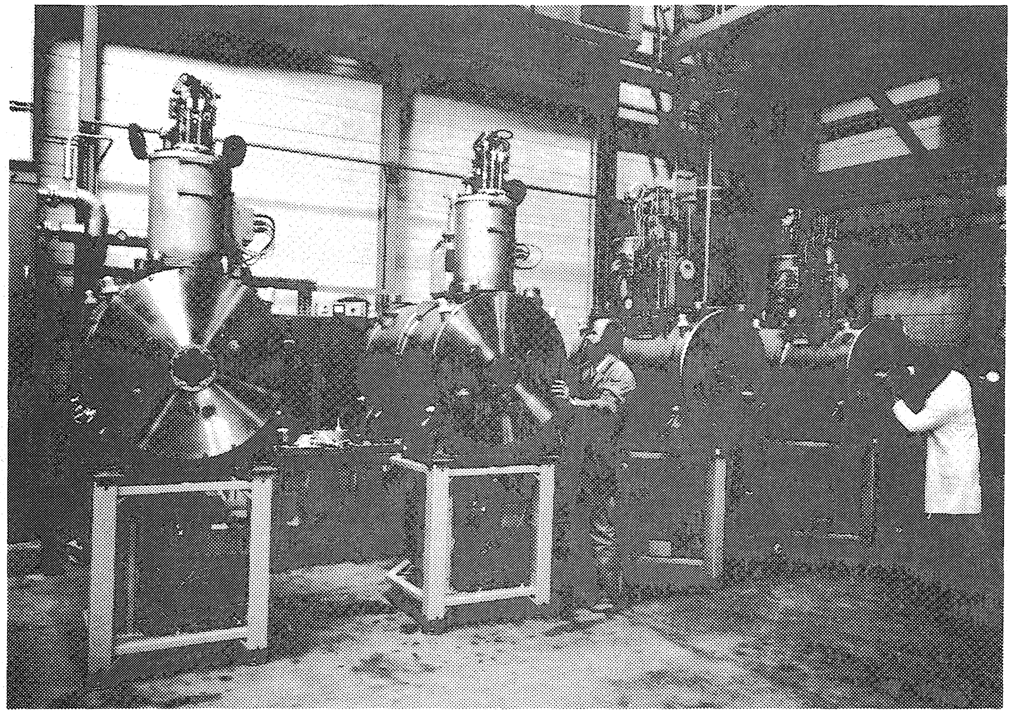

Fig. 3 Four quadrupoles ready for installation

3. RESULTS OF MAGNETIC MEASUREMENTS

The measurements were based on the rotating coil method. The measuring tube, composed of three independent coils, was aligned within ± 0.02 mm along the magnetic axis by a null method. In order to estimate the stability of the suspension system of the magnet, the measuring system was left mounted during a thermal cycle to room temperature and back to 4.2 K. The magnetic measurements showed a reproducibility of better than 0.01 mm. The positioning of the reference targets by optical means can add an error of ± 0.03 mm to the previous ones. By verifying the target position in a second series of tests, the maximum discrepancy ever found was 0.07 mm.

The field gradient obtained is 43.0 T m^{-1} at 1600 A over magnetic lengths of 0.67 m and 1.16 m for short and long magnets, respectively. The sextupole component is approximately 22 T m^{-2} at 200 A with magnetic lengths of 0.72 m and 1.30 m.

Due to yoke saturation, the 12-pole coefficient varies with the gradient level. The 12-pole winding compensates this effect. By appropriate 12-pole correction, the relative gradient errors in the useful aperture are kept below the tolerated limit of 10^{-3} at all excitation levels. The relative gradient corrections needed at the horizontal aperture limits of ± 65 mm are quoted in Table ~~1~~2. The difference in average values between short and long quadrupoles reflects the different relative influence of the end effects. The spread in the figures for each type of quadrupole at equal excitation results from the tolerances on overall geometry and on magnetic properties of the components. All these corrections require currents of less than 32 A in the dodecapole windings, which are well within their operating range. The resulting patterns of the integrated gradient errors are shown in Fig. 4 for the best and the worst quadrupole. The curves for all others are comprised between these extremes. All of them meet the requirements of the insertion.

Table 2

Required gradient corrections by dodecapole windings
at the aperture limits (± 65 mm)

$\Delta G/G \times 10^{-3}$ at ±65 mm / Excitation currents	Short quadrupoles				Long quadrupoles			
	SL1	SL2	SL7	SL8	SL3	SL4	SL5	SL6
1600 A					+1.7	+0.1	+0.4	+0.1
1500 A	+3.7	+1.9	+1.3	+3.3	+1.5	-0.1	+0.3	0
1300 A	+3.4	+1.4	+0.9	+2.8	+1.0	-0.6	-0.2	-0.6
1000 A	+2.4	+0.1	-0.4	+1.6	-0.1	-1.9	-1.5	-1.9
700 A	+2.3	-0.4	-0.8	+1.0	-0.6	-2.4	-2.0	-2.5
400 A	+2.6	-1.0	-1.2	+0.7	-1.0	-2.8	-2.3	-2.8

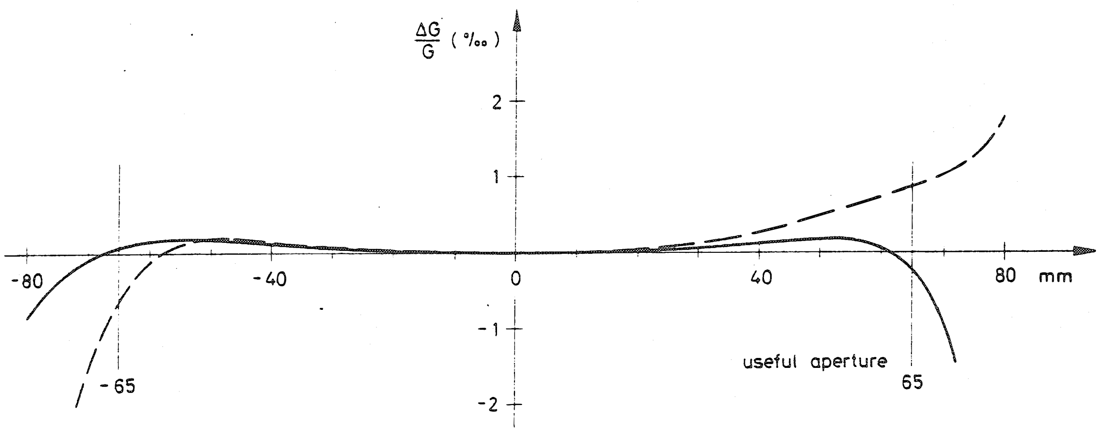

Fig. 4 Extreme patterns of integrated gradient errors

* * *

REFERENCES

1. J.P. Gourber, E. Keil, S. Pichler, The first high-luminosity insertion in the ISR, IEEE Trans. Nucl. Sci. NS-22, No. 3, p. 1419 (1975).

2. J. Billan et al., A superconducting high-luminosity insertion in the Intersecting Storage Rings (ISR), IEEE Trans. Nucl. Sci. NS-26, No. 3, p. 3179 p. 3179 (1979).

3. R. Perin, T. Tortschanoff, R. Wolf, Magnetic design of the superconducting quadrupole magnets for the ISR high-luminosity insertion, Div. Report CERN ISR-BOM/79-2 (1979).

4. R. Perin, Mechanical stability of superconducting quadrupole coils, Proc. 5th Int. Conf. on Magnet Technology, Rome, p. 559 (1975).

5. J. Billan et al., Construction of a prototype superconducting quadrupole magnet for a high-luminosity insertion at the Intersecting Storage Rings, CERN 76-16 (1976).

6. W. Ansorge et al., The prototype superconducting quadrupole magnet for the CERN-ISR, Proc. 6th Int. Conf. on Magnet Technology, Bratislava, p. 480 (1977).

7. H. Laeger, Ph. Lebrun, P. Rohmig, Eight liquid helium cryostats for the superconducting magnets of the ISR high-luminosity insertion, Proc. 8th Int. Cryogenic Engineering Conference, Genoa (1980).