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FOR THE LEP LOW-BETA INSERTIONS

by

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Abstract: The prototype of the superconducting quadrupoles for the low-beta insertions at the LEP e^+e^- collider, presently under construction at CERN, has been successfully tested. This industry-built quadrupole, which has a warm bore of 130 mm and a magnetic length of 2 m, is required to provide a gradient of 36 T m^{-1} over a good field aperture of 100 mm in diameter. It achieved its maximum operating current without training. While retaining the main characteristics of its ISR predecessors, the design of this magnet also incorporates several novel features, due to constraints imposed by the environment of the LEP experiments. In particular, the quadrupole is slender, ironless, and has a horizontally-oriented cryogenic service funnel. Following a description of the major aspects of the design of the magnet, the results are given of the magnetic and cryogenic tests and measurements.

Introduction

In a colliding-beam synchrotron accelerator, the particle interaction rate at crossing points is increased by decreasing the amplitude of betatron oscillations in these regions. This improvement in so-called luminosity is achieved by strong local focusing, known as a low-beta insertion, using powerful quadrupole magnets. In the case of the Large Electron Positron collider (LEP) at CERN, the luminosity which can be expected using low-beta insertions based wholly on conventional quadrupoles, can be doubled by making the last magnet superconducting [1]. The short focal length of this magnet means, however, that it is essentially embedded into the experimental detector; at LEP, there are four such detectors, each of which uses a large solenoid coaxial with the circulating beams for magnetic spectrometry. This proximity imposes unusual design constraints on the quadrupoles, so before embarking upon the production of the eight units required (one for either side of each experiment), a prototype has been built and tested.

1. Main Features of the Quadrupole

1.1 General design

The main design parameters of the quadrupole are given in Table 1. The requirement for the characteristics indicated in this table arose from a detailed parameter study of the LEP low-beta insertions [2], which took into account the recent achievements regarding superconducting quadrupole magnets, in particular those successfully employed at the CERN-ISR [3].

The relatively slow ramp rate renders possible the use of monolithic multifilamentary conductor with a design current small enough to limit cryogenic load, yet sufficiently large to keep peak quench voltages within the windings to reasonable levels. These considerations led to the choice of copper-stabilized NbTi conductor having the same specification as that used for the ISR quadrupoles. Besides having a cross-section close to the optimum for satisfying the requirements, this conductor benefitted from a fully characterized and tested insulation system [4]. Its main characteristics are given in Table 2.

The corners are rounded with a radius of 0.5 mm. The 0.10 mm thick insulation consists of a

Table 1

Design Parameters

Nominal gradient (for 65 GeV beams)	36	T m^{-1}
Minimum operational gradient	10	T m^{-1}
Magnetic length	2	m
Good field aperture (diameter)	100	mm
Tolerance on integrated gradient (at limit of useful aperture)	0.2	%
Minimum clear aperture (background)	120	mm
Length of cryostat (along axis)	2.5	m
Maximum superimposed field	0.6	T
Maximum ramp rate	0.3	$\text{T m}^{-1} \text{ s}^{-1}$
Nominal current	1625	A
Peak field in winding (at nominal current, with external field)	4	T
Stored energy (at nominal current)	310	kJ
Maximum test current	2000	A
Warm bore (inside diameter)	130	mm
Inner coil diameter	180	mm
Outer coil diameter	240	mm
Maximum tilt of magnet in service (transverse or longitudinal)	1.5	%

Table 2

Conductor Characteristics

Cross-section (matrix)	1.8 mm × 3.6 mm
Number of NbTi filaments	2230
Diameter of filaments	37 μm
Twist pitch	50 mm
Copper to superconductor ratio	1.7

phenolic modified PVA enamel covered with a polyimide film, wrapped as a single layer on the enamel and glued to it by ester-imide resin.

Figure 1 shows a transverse cross-section of the magnet in its horizontal cryostat. Working outwards, the main components are seen to be as follows: warm bore, inner wall of the helium vessel, coils, stainless steel stiffening quadrants, aluminium alloy shrinking rings, outer shell of helium vessel, heat screen and vacuum tank. Small channels for helium circulation are provided between the glass-fibre bandages separating the main windings from the stiffening quadrants and along the inside of these quadrants.

Coil integrity in operation is ensured by the application of suitable pre-compression. This is achieved by means of the shrinking rings, via the stiffening quadrants and the glass-epoxy bands. The coils are not supported inside; an annular space of about 1 mm is kept free between them and the cold bore. The external radial pressure is thus completely transformed into circumferential compressive stress in the compact coil structure, which prevents the coil from undergoing tensile strain when the electromagnetic forces are applied [5]. The stiffening quadrants serve to spread the radial forces when the magnet is powered, and to impart longitudinal rigidity to the complete structure.

Fig. 1 Transverse Cross-Section of the Magnet in its Cryostat

The finished magnet is shown in Fig. 2. Its total mass is 1500 kg, of which 1050 kg is cold.

1.2 The coils

Each of the four main coils consists of two blocks of insulated conductor separated by metal spacers. There are in total 184 turns, continuously wound in radial layers of eight turns and grouped in two blocks of seven and sixteen (2×8) layers. Shape,

dimensions and position of the blocks were optimized by computations for the required field distribution. The central post is made of austenitic stainless steel and the other wedge-shaped coil spacers of copper. The ends of the coils are of a modified constant perimeter shape. In order to achieve the required accuracy of ± 0.1 mm in azimuthal block positions, fibre-glass shimming is used to compensate for mechanical tolerances on spacers, conductor and winding. Each coil is separately impregnated under vacuum with epoxy resin. The accuracy of the $\pm 45^\circ$ faces is ensured by machining thin copper spacers which are glued to the potted coils; the four coils are then assembled together and wrapped with bands of epoxy-glass tape to form a cylindrical body which is subsequently ground to final diameter.

1.3 The clamping structure

The magnet clamping structure consists of four 30 mm thick cylindrical quadrants of stainless steel held in compression against the coil by means of ten 15 mm thick wrought aluminium alloy shrinking rings. The quadrants are separated from each other by 2 mm wide gaps and are bolted together to provide approximately 15 % of the prestress before fitting the rings. During this operation, the modulus of the coil is measured and the required interference between aluminium rings and structure calculated to provide an azimuthal prestress of about 3 daN mm^{-2} in the coil, at room temperature. At lower temperatures, the insulation and resin potting can withstand greater stress, and the greater coefficient of contraction of the aluminium increases the prestress in the coil to about 5 daN mm^{-2} , which is sufficient to maintain it wholly in compression up to currents in excess of 2000 A.

1.4 The cryostat

The magnet is cooled by pool boiling helium at about 4.25 K. All boil-off gas is used to reduce

Fig. 2 The Finished Prototype Magnet Under Test at CERN

the main heat inleaks to the liquid bath by cooling the current leads, the screen and the service funnel housing cryogenic and electric connections to the magnet. Only one cryogen is used and the boil-off gas is recovered at room temperature. Successive baffles installed along the horizontal service funnel limit losses in that region.

The cryostat enclosures consist of cylindrical vessels with flat end plates. The design pressure of the liquid helium vessel is 4 bar, both to accommodate the pressure rise following a magnet quench and to simplify cooldown. Welded seams are used throughout to ensure leaktightness of the helium vessel. Thermal insulation is achieved by the use of a vapour-cooled heat screen and 30 layers of aluminized Mylar* superinsulation. As the space available around the warm bore is limited, only superinsulation is used there. Aluminized Kapton* (45 layers) was chosen to withstand heating of the warm bore during bakeout of the beam pipe [6].

The magnet is suspended via short axles at its quarter points by tension rods to the reinforced vacuum enclosure. In order to preserve alignment when the magnet is tilted, the top axles are held in position with respect to the vacuum vessel by pretensioned wires. A horizontal column at the rear end defines the longitudinal position of the magnet. For transportation, the magnet is supported by a set of retractable blocking devices, calculated to withstand accelerations of up to 2 g.

The material used for the cryostat is mainly AISI 304L stainless steel, specified as being selected to have low permeability. The tubes inside the magnetic bore are of AISI 304LN (cold bore) and AISI 316LN (warm bore) grades in order to guarantee a magnetic permeability of less than 1.025 under operating conditions. Inconel 718 is used for the main suspension rods.

2. Results of Tests and Measurements

2.1 Training and performance

During the first test in a vertical cryostat at the manufacturer's premises, the design current (1625 A) was obtained without quench, and a value of 2000 A was reached after one quench. In Fig. 3, the specified critical current (short samples) is shown for fields perpendicular and parallel to the broad face of the conductor. The conductor used for the prototype

Fig. 3 Critical Currents and Load Lines

* Registered trade marks of Du Pont de Nemours.

was very slightly better than this specification. Two load lines are drawn in the graph representing the maximum field in the windings with and without the superimposed field of 0.6 T due to the detector magnet. Tests to date have been performed without the superimposed field, the maximum excitation current of 2000 A producing a peak field in the winding of 4.1 T and a stored energy of 465 KJ.

The magnet was then mounted in its horizontal cryostat, transported to CERN and retested. After quenching at 1905 and 1960 A, it reached 2000 A repeatedly without further quenches. A number of quenches were artificially provoked at 1900 A and 2000 A for test purposes, and the magnet was run for several hours at 1900 A both before and after one cycle to room temperature.

2.2 Inductance, energy dissipation and temperature rise

The inductance of the magnet is 232 ± 2 mH, independent of current. In operational conditions, should a quench occur, all the energy stored in the magnet is dissipated in the windings. For ease of ramping, no protection resistor is placed across the terminals inside the cryostat; possible damage due to eventual burnout of the current leads [7] is limited by interlocking the power supply with signals derived from a constant monitoring of lead resistance and temperature. For test purposes, however, a 0.17Ω resistor could be used for energy extraction. A measurement of the voltage across this resistor during the discharge of the magnet showed that about 65 % of the stored energy could be extracted after a 2000 A quench. The measurements of the current decay and the time of the start of the quench were used to compute the maximum temperature in a quenching coil [8]. Table 3 shows the relation between excitation current, I, stored energy, Q, maximum voltage per pole, V_{max} , and maximum temperature, T_{max} , at typical quenches. The relatively high hot spot temperature for natural quenches without energy extraction is due to slow propagation (some tenths of a second) between poles.

Table 3

Typical Quench Characteristics

	I (A)	Q (kJ)	V_{max} (V)	T_{max} (K)
Unprovoked quench without extraction	1960	445	147	200
Unprovoked quench with extraction	1905	421	80	96
Provoked quench with extraction	1900	419	80	84

2.3 Magnetic measurements

The measurements were performed with a coil of 2.978 m length, together with two 0.748 m long end coils, on a cylinder of radius 59 mm, according to a previously described method [9]. The reproducibility of the measurements is $2 \cdot 10^{-4}$ for the integrated gradient strength and $1 \cdot 10^{-4}$ for the harmonic content expressed as gradient error at the radius of the measuring cylinder.

The central field is deduced by subtracting the end measurements from those obtained with the integral

coil. The magnetic length was found to be a constant 1.995 m at all current levels, and the gradient 35.74 T m⁻¹ at 1625 A.

The harmonic content in terms of gradient error is given in Table 4:

Table 4
Relative Error on Integrated Gradient
(at 50 mm Radius)

multipole	right	skew
6-pole	-0.0002	-0.0009
8-pole	-0.0003	0.0003
10-pole	0.0005	0.0010
12-pole	-0.0041	0.0002
14-pole	0.0002	0.0001
16-pole	-0.0000	0.0003

It has also been verified that the integrated values of higher order multipoles (up to 36-pole) are negligible. The somewhat large dodecapole component is consistent with a measured systematic 0.15 mm azimuthal displacement of the large coil blocks towards the central post, and a combination of small random errors, accentuated by the effect of the relative permeability of the stainless steel posts (measured to be about 1.015 at 4.2 K). This error will be corrected in the series magnets by the removal of one turn from the small coil block.

The magnetic measurement system was also used to determine the position of the magnetic axis and median plane of the magnet [9]. It was confirmed that the position of the magnet with respect to the external references does not change when the magnet is tilted.

2.4 Cryogenic performance

Cooldown was achieved by forced circulation of cold gaseous helium. The temperature of the gas was reduced gradually in order to follow magnet cooldown and avoid thermal shocks. Cooldown took less than 20 hours, with a peak temperature difference between magnet and gas of 50 K, and a maximum temperature gradient in the magnet of 60 K m⁻¹.

Heat inleaks to liquid helium have been evaluated by measuring the boil-off rate of the cryostat at different LHe levels, with and without liquid transfer, and at endurance (1900 A) and zero currents. The cryomagnet shows a heat load at nominal level, zero current of 11 W. An indirect estimate of the heat load of the cryostat alone (i.e. excluding current leads) is then about 6 W of which half comes from the horizontal service funnel. The total heat load at 1900 A current, measured during the endurance test, amounts to 13 W.

Pressure release behaviour at quench was fully satisfactory. The quench relief device, a full-lift spring-loaded safety valve with an orifice cross-section of 616 mm², was set at 3 bar nominal. This proved to be adequate for discharging the helium flow vaporized upon magnet quenches, limiting the pressure in the cryostat to 3.5 bar. Very little helium was in fact discharged (a few cubic metres NTP) and most of the helium inventory in the cryostat (45 l) was recovered through the normal outlets.

Longitudinal and transverse tilts corresponding to those encountered in LEP (1.5 %) have been applied to the cryomagnet: no significant effect was observed.

The horizontal service funnel did not perform as well as expected from previous model tests: icing of the terminal flange occurred and was compensated by installing a heater in the O-ring zone. This problem is attributed to convection currents inside the service funnel due to excessive clearance between the baffles and the funnel wall. In the series cryostat, this point will be remedied by adding a flexible seal around the baffles.

Conclusion

The results of tests and measurements which have been made on the prototype quadrupole have amply demonstrated the soundness of its design and the suitability of the manufacturing methods employed. Production of the eight series units by Alstom, France, is proceeding according to plan.

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The magnet was carefully crafted by Alstom, Belfort, France.

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