Construction and Test of Superconducting Quadrupoles for the LEP2 Low-Beta Insertions

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Abstract

The electron-positron collider LEP at CERN is equipped with powerful and compact superconducting quadrupoles embedded in either side of the four experiments. For the second phase of LEP, where the beam energy is raised from 65 GeV to above 90 GeV, the eight magnets are to be replaced by more powerful units, capable of providing a gradient of up to 60 T/m in a warm bore of 120 mm diameter. The design of these new low-beta magnets has been reported elsewhere [1]. The techniques for producing these magnets and the results of the measurements are described.

1. INTRODUCTION

In LEP, the beam luminosity at the experimental crossing points is enhanced by the use of low-beta quadrupoles which squeeze the beam cross section. The last and crucial element is a vertically focusing quadrupole which must be superconducting in order to achieve the required gradient, and iron-free to allow its installation in the field of the solenoid spectrometer magnets. The upgrade of 65 GeV to over 90 GeV called for 50% stronger quadrupoles. Thanks to the improvements in the performance of superconducting material this could be designed to fit into the previously occupied space. Now ten such magnets have been built (one prototype and nine series units) of which nine have been tested and four are already operational in LEP.

2. MAGNET DESCRIPTION

The magnet is a 2 m long quadrupole coil assembly without any iron yoke [1]. It is bath cooled and mounted in a close-fitting horizontal cryostat [2]. The coils (see Table 1) are wound from monolithic NbTi superconducting wire. The bare wire is insulated with wrapped polyimide. Each coil consists of two rectangular coil blocks wound around a central island of stainless steel. The longitudinal spacers are made from copper and the end spacers moulded in bronze; these are insulated with glass-fibre epoxy sheet. The quadrants are epoxy impregnated and then assembled on a mandrel and banded with pre-impregnated glass-fibre tape. Each coil assembly is prestressed by means of shrink-fitted aluminium rings. The magnet is first trained in a vertical cryostat to an excitation above the nominal current. After that it is mounted on three feet in a helium vessel and this vessel is hung by means of Inconel® rods inside the vacuum vessel. The leads are brought out through a horizontal service funnel.

Table 1: Magnet characteristics

Coils		
Nominal gradient	60	T/m
Nominal current	1900	A
Peak field in winding	5.7	T
Diameter useful aperture	100	mm
Inner coil diameter	160	mm
Outer coil diameter	209.6	mm
Magnetic length	2	m
Inductance	0.28	H
Operational gradient	11-55	T/m
Wire		
Metal cross section	1.5 x 2.95	mm
Copper to NbTi ratio	1.7	
Diameter filaments	40	µm
Insulation material	Polymide tape	
Insulation thickness	3 x 25	µm
Critical current at 4.3 K	2300	A

3. MANUFACTURE AND TESTS

The coils have been wound on a computer controlled winding table which was programmed during the winding of the first coil to stop at the precise positions where joggles have to be made. The winding tension was modulated from 330 N for the first block to 165 N for the last block in order to obtain a roughly uniform wire tension of 160 N (tensile stress ~40 N/mm^2). The impregnation of the coils was checked by cutting a first prototype coil. It appeared that the epoxy glued correctly the wires together through their polyimide insulations but it did not penetrate in between the insulation and the metal wire. This leaves the wire free to slide through the two-third overlapped insulation and avoids local stress concentrations. In fact, taking a slice of this prototype coil, we could easily push the wires out of their insulation leaving behind a honeycomb of polyimide band. The wire of magnets 1 to 9 was insulated with Upilex® and that of magnet 10 with Kapton®

The coils were assembled on a mandrel. The gap between the coils was shimmed with copper spacers. Then the mandrel was slightly released and the coil was banded with the prepreg glass tape creating a first compression of the coil. After curing of the tape, the coil was turned to a precise diameter. Before determining the shrink ring interference, the coil was locally compressed with a given pressure and the corresponding radial compression measured to obtain an indication of the coil modulus. The interference (typically

0.6 mm on the diameter of 220 mm) was then chosen to obtain a radial pressure of about 8 N/mm^2 on the coil giving an average azimuthal prestress in the coil of 35 N/mm^2.

After training the magnet in a vertical cryostat to 1900 A, it was built into the helium tank and this assembly was mounted into the insulation vacuum tank. The welds of the helium tank were thermal-shock tested by spraying liquid nitrogen over the welds. The vessel was then pressure tested and tested for helium tightness.

The finished magnet was shipped to CERN where it was tested further to complete the training and to make the magnetic measurements.

4. TEST RESULTS

The short sample current of the wire was measured by the manufacturer and from the results we might have expected to reach the short sample limit between 2275 A (magnet 6) and 2415 A (magnet 10).

4.1 Training quenches

The results of the training of the magnet in the vertical test cryostat at the manufacturer's as well as at CERN in the final horizontal cryostat are shown in Fig.1. The best magnet trained to 1900 A in 6 quenches (magnet 3) and the worst in 22 quenches (magnets 6 and 10; the latter had the best short sample expectations). No correlation could be found with the level of prestress in the coils. The shrink ring diameters were measured to deduce the radial pressure on the coils which ranged from 6 to 21 N/mm^2 yielding azimuthal prestresses of 27 to 93 N/mm^2. The least as well as the most training magnet are both situated at minimum average prestress. The first magnet was re-shrunk obtaining the peak prestress of 93 N/mm^2 but its training continued as before.

Tests with detection antenna coils have shown that

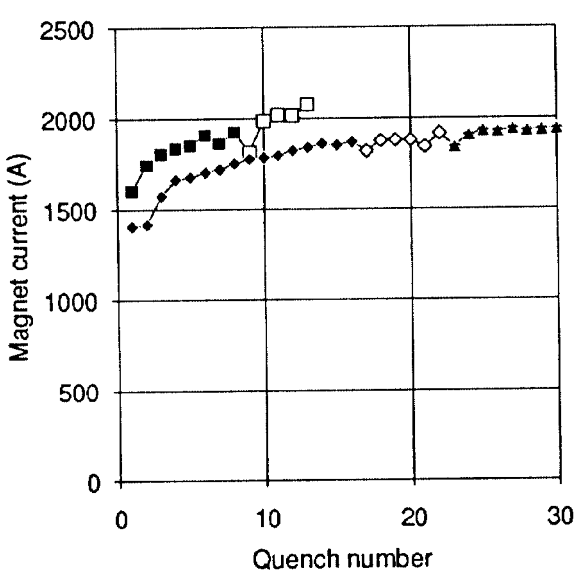

Fig. 1. Training of magnets
Top line: magnet 3 (best) Bottom line: magnet 6 (worst)
(Different symbols for different heat cycles)

quenches were probably not provoked by movements of the coil ends.

A change of bath temperature of 0.5 K, expected to change the short sample current by 200 A, did not change the level of the training quenches. A study has been made to see if the training behaviour could be caused by slip friction near the coil ends. It appeared that although there could be a considerable slip between the wires near the coil ends, the frictional energy is probably not sufficient to cause magnet quenches. The training of the magnet seems to advance more slowly when it reaches a current level of 1800 to 2000 A. It may be a coincidence, but at this level the wires which lose some prestress in the cooldown, reach again the tension "frozen" in the coil during the impregnation.

Repeated tests after a heat cycle, whether done at the manufacturer's or at CERN after assembly in the horizontal cryostat and the transport, showed in general one retraining quench before continuing the training where it was stopped before. An exception was magnet 10, which showed a very slow training, with the usual single retraining quench after a heat cycle at the manufacturer's, but after the assembly and shipment to CERN some 10 retraining quenches were necessary to obtain the previous current level. After a heat cycle at CERN it showed no retraining.

It should be noted that these magnets, with dry-wrapped insulation did not train less than the previous series [3] which featured glued enamelled conductors.

4.2 Quench behaviour

All the poles quenched; there was no preference for a particular pole to quench except for two magnets, numbers 2 and 6, where the second pole was dominant, quenching 55% and 80% respectively of all their training quenches.

A part of the magnetic energy was extracted by switching a dump resistor in the circuit as soon as the quench started. At the manufacturer this was a 150 mΩ resistor which together with a 500 mΩ safety resistor on the magnet extracted about 88 kJ when switched on after about 70 mseconds. At CERN there was just a dump resistor of 167 mΩ extracting some 145 kJ when switched after 50 mseconds. The peak temperatures in the coil, deduced from the MIIT's were typically 100 to 150 K. The inductive coil voltages where determined by the extraction resistor and approached 100 Volt. The resistive coil voltages ranged from 0 to 100 Volts but on two occasions an exceptional 200 Volts was recorded.

An advantage of switching the external resistor in the circuit is the effect of quench back caused by the rapid reduction of field. This makes all the poles quench and thus reduces the peak temperatures and voltages. The effect has been checked by switching the resistor in the circuit at different current levels and record the amount of extracted energy. Fig.2 shows how at low current, all the energy is extracted because none of the coils quenches. At higher current however, one can see that a part of the energy is not extracted but dumped in the magnet as the coils quench and become resistive. This is confirmed by the reduced unloading time due to the increased circuit resistance of the dump resistor and the coil resistances.

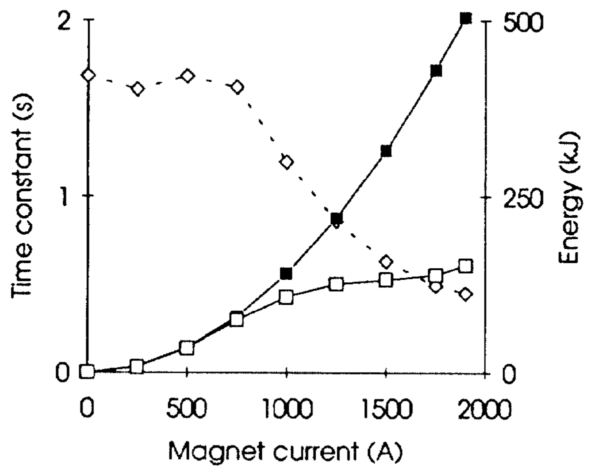

Fig. 2. Quench back when unloading over dump resistor
Unloading time constant (dotted line)
Magnetic energy (black squares)
extracted energy (white squares)

4.3 Magnetic measurements

The transfer function for the different magnets is in the range from 62.95 to 63.33 T/kA. The multipolar field contents measured at 1825 A are given in Fig.3, together with the spread between the different magnets. No adjustement of the coil geometry was required following the measurement of the prototype.

The first natural multipole G_6 defined here as dB_6/dR, was eliminated in the coil optimization, so its appearance betrays errors in coil geometry. There is little correlation between the thickness of the coil quadrant spacers and this 12-pole component except for magnet 2, where very thin spacers resulted in a high G_6 multipole and a high transfer function.

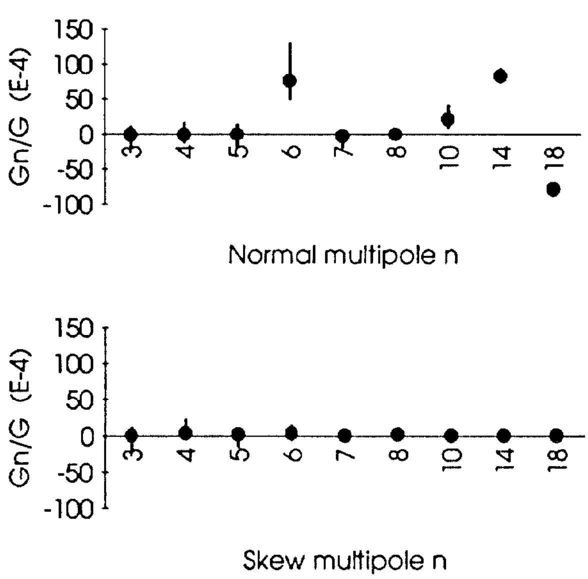

Fig.3. Integrated multipoles measured at radius 59 mm (relative gradient errors)

The magnetic field shows a hysteresis. When the magnet is cycled from 0 to 1825 A and back the transfer function as well as the G_6 multipole are lower than nominal at rising field and higher than nominal at decreasing field by the amount given in Table 2.

Table 2: Hysteresis effect during complete excitation cycle

	Transfer function	G_6/G multipole
at 325 A	+/- 0.16	+/- 80 10^{-4}
at 400 A	+/- 0.11	+/- 60 10^{-4}
at 800 A	+/- 0.03	+/- 20 10^{-4}

There is no typical time dependence of the multipoles which vary in one hour time by less than 5% in a non-systematic way.

4.4 The cryogenic performance

Cooling down from 300 K to 18 K takes about 48 hours. Filling the cryostat with liquid helium takes some 3 hours and after each quench it takes 1.5 hours to fill the cryostat again. The heat loss including that of the current leads at zero current is about 20 Watts. The floating radiation shield reaches its equilibrium temperature after a few days.

5. CONCLUSIONS

Ten low-beta quadrupoles have been successfully built and tested in industry. The field quality of all these magnets is as desired. The magnets show significant training above 80% of short sample current, the cause of which has not been identified. Four magnets have been installed in the LEP machine and perform satisfactorily. Four other magnets will be installed in LEP at the end of this year.

6. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the work of D. Coxill and D. Landgrebe (Tesla Engineering) and of H. Blessing, R. Chanut, H. Depierre, J. Mazet, G. Peiro, D. Regin, J. -L . Servais and G. Trinquart (CERN).

7. REFERENCES

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