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by

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Abstract: The series production of a total of 814 quadrupole magnets of two different types is approaching its end and that of a total of 510 sextupole magnets, also of two different types, is already finished.

After a review of the design of these lenses, the experience gained during their manufacture is discussed. The results of the systematic measurements of their excitation characteristics and field quality are presented and linked to the quality of the low-carbon steel sheet used for their magnetic circuits and to that of the geometry achieved in the assembly of the magnets.

Introduction

The LEP magnet system [1] contains 1312 quadrupole and sextupole magnets to provide the required focusing of the beams. The main nominal characteristics of these lenses are shown in the table below.

Table 1

Main Characteristics of Quadrupoles and Sextupoles

	Quadrupoles		Sextupoles	
Magnet type	MQ	MQA	MSF	MSD
Total number of magnets	520	288	248	256
Magnetic length (mm)	1600	2000	400	760
Maximum gradient ($T\ m^{-1}$)	9.5	10.9	--	--
Maximum d^2B/dx^2 ($T\ m^{-2}$)	--	--	180	180
Inscribed circle diameter (mm)	125	125	150	150
Steel length (mm)	1550	1950	370	730
Pole width (mm)	112	120	70	70
Total steel mass (kg)	2500	3600	420	800
Total number of turns per pole	29	58	31	31
Al conductor cross-sectional area (mm^2)	194*	130*	130*	130*
Resistance at 20 °C ($m\Omega$)	65	250	77	47
Maximum current (A)	525	320	360	360
Mass of aluminium conductor (kg)	235	344	78	121

* hollow conductor

° anodized aluminium strip

In the regular lattice of the LEP arcs, 240 and 248 MQ magnets are connected in series to form the horizontal focusing (F) and defocusing (D) circuits, respectively. Next to them are located the MSF and MSD sextupoles, grouped in circuits consisting of about 20 magnets each. The excitation current for all these magnets is mainly carried by a bus-bar system.

The MQA quadrupoles, used in the dispersion suppressor and acceleration lattice cells, are grouped in 118 independent circuits, each requiring long cable runs.

1. Basic Requirements

Beam optics, availability of longitudinal space and the cross-section of the vacuum chamber have dictated, together with the technological feasibility and economical aspects, the basic magnet parameters, such

as maximum gradients, magnetic and iron lengths, and the number of ampere-turns. The size of the good field region (118 mm horizontally by 66 mm vertically) and the stringent tolerance on field quality [2] over the whole excitation range imposed the minimum pole width, the choice of fully symmetric magnetic circuits and the definition of the tolerances on their symmetry. Concerning the latter, it was required that at any axial position the distances between the corners of adjacent poles be within ± 0.1 mm of the nominal value and the difference between the largest and the smallest of these values be smaller than 0.1 mm. The admissible spread in the quadrupole strength ($5 \cdot 10^{-4}$ r.m.s.) led to fixing tight tolerances of ± 0.08 mm for the inscribed circle diameter and of ± 0.5 mm for the steel length of the relatively long MQ and MQA magnets. For the sextupoles, where the admissible spread in field strength set by beam optics considerations was larger ($4 \cdot 10^{-3}$ r.m.s.), it was found technically reasonable to fix the above tolerances to ± 0.1 mm and ± 0.5 mm, respectively. Furthermore, to respect the limits on the spreads in quadrupole and sextupole strengths, the packing factor must be reproducible to ± 0.3 % and ± 0.5 %, respectively.

Hollow aluminium conductor for directly water-cooled excitation coils was also a mandatory requirement because of the choice of aluminium for the excitation bars of the LEP dipoles and the evident convenience of a common cooling system.

2. Design Features

For all types of lenses, the required length and strength were such that parallel side poles and hence easy to manufacture race-track shaped coils could be designed.

2.1 Coil design and choice of current density

Considering the large number of coils to be manufactured, some effort was made to find a coil design which would be cheaper than the classical one making use of hollow conductor.

A novel design using anodized aluminium strip as conductor, which simplifies coil winding and gives a higher filling factor with respect to traditional coils, was developed and its feasibility and reliability successfully proven [3]. For each magnet type, both coil designs were studied and optimized taking into account the capital cost of coils, magnetic circuits, power supplies and cooling, and the operational cost for 30 000 hours at 85 GeV of the power taken from the grid (including 17 % power dissipation for losses in power distribution and conversion, and cooling). With the assumed costs, optimum current densities turned out to be about $1.8\ A\ mm^{-2}$ for the hollow aluminium conductor and about $1.5\ A\ mm^{-2}$ for the alternative design. It is worth noting that the optima found are rather flat (a variation of $\pm 0.1\ A\ mm^{-2}$ corresponds to a few percent variation in the total system cost, capital plus operation) and that the costs of power and coils are by far the dominant ones.

After competitive tendering, it turned out that for the approximately 30-turn coils of the MQ, MSF and MSD magnets the hollow-conductor coils led to the lowest overall cost, whereas the strip design was the more

economical solution for the 58-turn MQA coils, for which it led to a 30 % lower power dissipation, thanks to its high filling factor.

2.2 Pole profile and width

The pole profiles for each type of magnet were defined so as to compensate for the end effects and satisfy the field quality requirements for the integrated field. This approach avoids the machining of chamfers at the magnet ends and the associated loss of magnetic length. For the quadrupoles, a pole profile based on the ideal hyperbolic profile with tangent straight segments was defined by two-dimensional field computations so as to obtain 12 and 20-pole induced gradient errors ($\Delta G/G_0$) below $2 \cdot 10^{-4}$ at the limit of the useful field region.

A model quadrupole with the above pole profile was ordered to assess also the manufacturing methods for the yoke and coils. After measurement of the 12 and 20-pole gradient errors introduced by the end fields and appropriate scaling [4], 12 and 20-pole field components creating a $\Delta G/G_0$ at $x = 59$ mm, $y = 0$ mm, of +0.87 % and -0.1 %, respectively, were introduced in the pole profile of the 1.55 m long, $\varnothing 125$ mm series prototype MQ quadrupole. This was done by modifying accordingly the pure hyperbolic profile by iterative computations. The same procedure was then applied for the 1.95 m long MQA quadrupole, where 12 and 20-pole field components leading to a $\Delta G/G_0$ at $x = 59$ mm, $y = 0$ mm, of +0.66 % and -0.12 %, respectively, were introduced in the pole profile.

The pole width for the MQ quadrupoles has been determined so as to be the minimum necessary to satisfy the field quality requirements; that of the stronger MQA quadrupoles had to be made slightly larger in order to limit saturation at the pole root, as occurs with a parallel pole design.

As concerns the MSF and MSD sextupoles, the design of their pole profiles has been directly based on two and three-dimensional computations [5].

2.3 Magnetic circuit

The magnetic circuits are made of identical quadrants/sextants, each built from a stack of 1.5 mm thick laminations compressed between end plates and welded to a reinforcing profile.

The magnetic properties for the low-carbon steel sheet were defined following the specifications of the steel for ISR and SPS magnets. No steel shuffling or mixing was asked for. To build a quadrupole, the quadrants are assembled by means of clamps passing through notches located along the mating surfaces. These notches are created by flipping the laminations in groups of 20 during stacking, an operation which is in any case required to average out differences in the laminations' thickness and systematic punching errors of the pole profile. For the sextupoles, the sextants are welded together three by three, after mounting the coils, so as to form upper and lower sextupole halves, which are bolted together.

The reinforcing angles are dimensioned so as to limit the sag of individual stacks to below 0.05 mm to avoid any permanent deformation which might occur due to mechanical hysteresis because of friction between laminations during handling and assembly. The bolts clamping the stacks together are in turn dimensioned to apply each a 4 to 5 t force in order to flatten out any long wave deformation induced by the residual welding stresses. Straightness tolerances were specified to be

within ± 0.05 mm for the MSF and MSD sextants, ± 0.06 mm and ± 0.08 mm for the MQ and MQA quadrants, respectively.

3. Magnet Manufacture

Three different firms were entrusted with the manufacture and delivery of the MQ, MQA, MSF and MSD magnets. About one year was necessary to produce detailed manufacturing drawings and to design and manufacture the tools for series production. Punching dies stamping two laminations per press stroke were adopted to minimize the losses of steel sheet and to achieve sufficient production rates.

The quadrants/sextants required a careful running-in of their manufacture in order to respect the required straightness tolerances. Careful stacking and shimming, to keep the stack ends parallel to each other within a few tenths of a millimeter, minimum weld thickness, possibly stress-relieved reinforcing angles machined to accuracies below 0.1 mm and stiff enough to withstand the forces exerted by the welds, accurate welding procedures and last but not least, skilled personnel are all very important.

The running-in of the manufacture of the MQA coils has underlined the importance of the geometry of strip edges, of the cleanliness of the heat sinks, which had eventually to be anodized, and of the material for the coil fillers, which must match the thermal elongation of the whole coil beyond curing temperature. The winding time is about 5 h for a 29-turn MQ coil, 14 h for a 58-turn MQA strip coil, and only 15 and 30 min for the shorter MSF and MSD 31-turn coils, respectively, for which a nearly fully automated winding table was developed by the manufacturer.

Only a few percent of the MQA and sextupole coils had to be rejected due to interturn and ground insulation defects, mishaps during impregnation, obstructed cooling channels, etc.; a quasi-zero rejection quota was achieved for the MQ coils. It is also interesting to note that for the MQA soft aluminium strip coils, where the interturn insulation relies on the anodic coating and a 0.05 mm thick glass-fibre tape, interturn short-circuits only occurred on about 1 % of coil production, under normal (no clean area) electric shop conditions.

4. Results of Magnetic Measurements

The measuring system used is described in Ref. 6. The reproducibility of the measurements is of $2 \cdot 10^{-4}$ for the integrated field strength and $1 \cdot 10^{-4}$ for the harmonic content expressed as gradient error at the limit of the useful aperture.

4.1 Integrated field strength

The standard deviation of the integrated field strength (σ_s) and the ampère-turn loss (ΔAT) are shown in Figs. 1.a) to 1.c) for the different magnet types. The link between the higher loss of ampère-turns and larger σ_s is evident.

For the MQA quadrupoles, the fact that the standard deviation is also larger in the region where no ampère-turn losses occur, is mainly due to the steel sheet being delivered by two different manufacturers because of production difficulties at the originally chosen steel producer's premises. This situation could be accepted considering the large number of independent circuits, each containing only a few MQA magnets; the latter are chosen so as to limit the spread to below $5 \cdot 10^{-4}$ r.m.s. among the magnets of a same circuit.

a) Standard Deviation for MQ Quadrupoles

b) Standard Deviation for MQA Quadrupoles

c) Standard Deviations for the Sextupoles

Fig. 1 Standard Deviations of the Integrated Field Strengths (σ_s) for the LEP Lenses

The histograms concerning the coercivity, H_c , and MQA strength at $I = 140$ A are superimposed in Fig. 2 which also shows the correlation coefficient between the average H_c of the MQA magnets and their strength for various excitation levels.

Table 2 shows the average values and the standard deviation of core length, L_c , diameter of inscribed circle, d , and coercivity, H_c , of the different magnets.

As regards the MQ magnets, Fig. 3 shows the evolution of the correlation coefficients, k , linking L_c , d and H_c to the integrated quadrupole strength, $G\ell$, throughout the excitation range. It can be seen that $k(H_c, G\ell)$ is positive at low excitation (remanent field) and negative at higher excitation (lower permeability associated with higher H_c), $k(d^{-2}, G\ell)$ is maximum in the linear part of the excitation, whereas $k(W, G\ell)$ increases with excitation, W being the average core weight.

Fig. 2 Correlation between σ_s and H_c for MQA magnets

Table 2
Average values and standard deviations
of L_c , d and H_c

	MQ	MQA	MSF	MSD
$\bar{L}_c$ (mm)	1549.97	1950.69	370.15	730.03
$\langle L_c \rangle$	0.138	0.24	0.134	0.184
$\bar{d}$ (mm)	125.002	125.13	150.02	149.98
$\langle d \rangle$	0.0166	0.024	0.032	0.017
$\bar{H}_c$ (A m ⁻¹)	52.2	48.9	56.3	56.3
$\langle H_c \rangle$	3.4	9.5	6	6

Fig. 3 Correlation Coefficients for MQ Quadrupoles as a Function of Excitation Current

For the sextupoles, Fig. 4 shows $k_c(d^{-3}, G'\ell)$ and $k_c(L_c, G'\ell)$ as a function of excitation current; the lower values of $k(d^{-3}, G'\ell)$ at both ends of the excitation range are again linked to the major role played there by the magnetic properties of the steel.

Fig. 4 Correlation Coefficients for Sextupoles as a Function of Excitation Current

4.2 Field quality

For the quadrupoles (see Table 3), the errors due to 6-pole components, which are introduced by magnetic or geometrical asymmetries of one pole with respect to the other three poles, average to values near

Table 3

Field Quality of Quadrupole Magnets

$$G\ell = \int (dB/dx) d\ell ; e = \Delta G\ell / G_0\ell \text{ at } x = 59 \text{ mm, } y = 0 \text{ mm (in units of } 10^{-4})$$

Field component		MQ quadrupoles						MQA quadrupoles							
		Specified		I = 55 A		I = 522.5 A		Specified		I = 25 A		I = 170 A		I = 320 A	
		$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$
Normal	6-pole	6	12	-0.1	1.6	-0.8	3.9	6	15	-0.9	6.6	-0.5	2.9	-0.3	8.3
Skew	6-pole			-0.2	2.1	-0.1	3.7			-0.9	8.1	0.2	3.8	-1.6	9.3
Normal	8-pole	5	10	3.1	2.5	2.1	2.0	7.5	15	0.0	4.2	-0.7	3.9	-1.3	3.4
Skew	8-pole			1.0	1.3	1.1	0.7			0.1	1.6	0.2	1.1	0.2	1.1
Normal	12-pole	10	10	10.1	1.6	11.2	1.4	15	15	5.8	2.4	9.6	2.2	6.4	2.3
Normal	20-pole	--	--	-3.3	1.1	-6.5	1.1	--	--	-3.3	4.0	-4.3	4.0	-6.2	4.1

Table 4

Field Quality of Sextupole Magnets

$$G'\ell = \int (d^2B/dx^2) d\ell ; e = \Delta G'\ell / G_0'\ell \text{ at } x = 59 \text{ mm, } y = 0 \text{ mm (in units of } 10^{-3})$$

				MSF Sextupoles						MSD sextupoles					
Field component		Specified		I = 18 A		I = 180 A		I = 360 A		I = 18 A		I = 180 A		I = 360 A	
		$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$	$\bar{e}$	$\langle e \rangle$
Normal	8-pole	1.7	20	0.2	0.8	0.2	0.6	0.2	1.1	0.0	1.0	0.0	0.9	0.0	1.1
Skew	8-pole			-1.0	1.4	-0.7	1.0	-0.5	1.0	-1.2	1.2	-1.0	1.0	-0.7	1.0
Normal	10-pole	3.4	20	-1.7	1.5	-0.6	1.3	-0.8	1.3	-1.2	1.6	-0.2	1.3	-0.6	1.5
Skew	10-pole			-0.2	1.2	-0.1	0.8	-0.1	1.2	0.2	1.7	0.0	1.1	0.0	1.2
Normal	18-pole	16	20	2.0	0.7	2.7	0.6	1.7	0.6	0.0	0.6	0.7	0.5	0.1	0.4
Normal	30-pole	--	--	-2.7	0.3	-2.9	0.2	-3.1	0.2	-1.8	0.4	-2.0	0.3	-2.1	0.5

to zero, but show an increase in their standard deviation at low and high excitation values, as is clearly shown by the MQA measurements. This confirms that their origin is mainly due to steel properties; in the case of the MQA magnets, the importance of equipping the quadrants of a quadrupole with end plates of equal magnetic characteristics has been demonstrated. A few magnets with end plates having H_c -values differing by 15 to 20 % have shown 6-pole errors of up to $3 \cdot 10^{-3}$ at low and high excitation levels, and of only $5 \cdot 10^{-4}$ at medium excitation. These asymmetries have also been found to displace the magnetic axis by up to 0.15 mm. The errors due to the 8-pole components are mainly introduced by asymmetries between the quadrupole halves, i.e. the average distance between pole edges being larger in one symmetry plane. A too large systematic 8-pole error was corrected by increasing the number of clamping elements in the horizontal plane. Asymmetric field components higher than 8-pole have been measured to be negligible. The 12-pole field component has been controlled by the pole-profile design; for the MQ quadrupole, it has been purposely set near to its upper specified value so as to compensate the 20-pole field component in the horizontal plane, which is less easy to master within the given pole width and more sensitive to different induction levels in the pole.

With respect to the sextupole field quality (see Table 4), the presence of a skew 8-pole component could be linked to the higher stiffness of the lower magnet halves, where welded U-profiles act as feet, with respect to the upper halves. When bolting the two halves together, a slight rotation (some hundreds of a millimeter) of the upper poles occurs. The presence of a normal 10-pole component is believed to be due to the distance between upper and lower halves being slightly larger than the ideal value.

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