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# DESIGN OF THE SUPERCONDUCTING QUADRUPOLES FOR THE LEP200 LOW-BETA INSERTIONS

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# Design of the Superconducting Quadrupoles for the LEP200 Low-Beta Insertions

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**Abstract** - The low-beta insertions in LEP, the new $e^+ e^-$ collider at CERN, have been instrumental to the initial success of this machine. The most powerful focusing elements of the insertions are the eight 2 m long superconducting quadrupoles embedded into either side of the four experiments. These iron-free magnets were designed to give the highest gradient obtainable with industrially-proven technology at the time. In harmony with the other elements of the insertions they cover the first phase of operation of the accelerator, i.e. up to 65 GeV. Over the next years, the LEP200 project will take the machine energy up to above 90 GeV. In order to achieve this, the final quadrupoles must be strengthened. New quadrupoles have been designed for this purpose, and an order placed with industry for their fabrication. Thanks in part to the higher performance NbTi conductor now available, it has been possible to retain the external dimensions of the present units. Nevertheless, in order to achieve the required 50% increase in integrated gradient, a number of significant changes have had to be made to the design of the magnet itself. In this paper, we describe the magnetic and mechanical design of the new 60 T/m 120 mm diameter warm bore quadrupoles for LEP200.

## I. INTRODUCTION

In LEP, the large electron-positron collider recently commissioned at CERN, the luminosity is enhanced at the experimental crossing points by local reduction of the transverse dimensions of the particle beams by means of low-beta insertions. A crucial element in this optical arrangement is the last, vertically-focusing, quadrupole which must be superconducting in order to achieve the required gradient, and iron-free so as to allow its installation within the field of the solenoid spectrometer magnets. The layout of the present low-beta insertions is valid for the first phase of LEP, i.e. with beams of up to 65 GeV; the eight superconducting quadrupoles presently in operation were optimised accordingly. A project is now underway however to increase the energy to over 90 GeV. Among the many changes the low-beta insertions will be rearranged, and to obtain from them the same performance at the highest energy it is necessary to increase the strength of the quadrupoles by 50%.

## II. MAGNETIC DESIGN

The design of the magnets in use for the first phase of LEP has been reported previously [1] [2], and their demonstrated success has lead us to adopt a similar design for the new magnets, i.e. two-block coil geometry using monolithic multifilamentary conductor. The increased gradient is obtained by decreasing the inner coil bore diameter from 180 mm to 160 mm, and by increasing the current density; the effective length of 2 m is unchanged. The magnet parameters are given in Table 1.

Since the present magnets were specified, considerable progress has been made in the guaranteed performance of commercially available superconducting material. The conductor cross-section has thus been reduced, allowing an increase in the number of turns, and the nominal current has been increased. Its characteristics are given in Table 2.

The coil geometry has been simplified by rotating the large block to bring its faces parallel to the horizontal and vertical planes of symmetry. Selected quadrants will be assembled with specific parallel-sided shims, obviating the need to machine thin wedges.

In the field optimization unwanted higher multipoles (12-, 20-, 28-pole, etc.) have been suppressed to the level of less than 0.1% of the gradient at 50 mm, or of less than 0.01 % relative field error within the same aperture. These are judged to be acceptable, being small compared to the random multipole errors due to realistic mechanical tolerances as achieved on the first series.

TABLE 1
DESIGN PARAMETERS

| | | |
|---|---|---|
| Nominal gradient | 60 | $Tm^{-1}$ |
| Range of operating gradient | 11 - 55 | $Tm^{-1}$ |
| Effective length | 2 | m |
| Useful aperture (diameter) | 100 | mm |
| Clear bore | 120 | mm |
| Nominal current | 1950 | A |
| Peak field in winding (at nom. current) | 5.1 | T |
| Stored energy (at nominal current) | 400 | kJ |
| Inner coil radius (warm) | 80 | mm |
| Outer coil radius (warm) | 104.8 | mm |

TABLE 2
CONDUCTOR CHARACTERISTICS

| | |
|---|---|
| Cross-section (matrix) | 1.5 mm x 2.95 mm |
| Copper to NbTi ratio | > 1.6 : 1 |
| Number of filaments | > 2000 |
| Diameter of filaments | < 40 μm |
| Twist pitch | 50 mm |
| Polyimide insulation thickness | 75 μm |
| Critical current at 5 T, 4.3 K | > 2700 A |
| Critical current at 6 T, 4.3 K | > 2200 A |

## III. MECHANICAL STRUCTURE

The electromagnetic forces in the new series of magnets are 75% higher than in the previous series. In order to achieve the prestress required to maintain the coil blocks in compression, it has been necessary to make significant changes to the coil support structure.

As the new magnets have the same effective length as the ones in use at present, the satisfactory experience with the cantilever support has lead to the choice of "plug-in" units having the same outer envelope. The space obtained by reduction of coil dimensions can thus be wholly used to increase the stiffness of the coil support structure. The structure has been further stiffened in the radial direction, and simplified, by the use of thick aluminium shrink rings instead of a combination of longitudinal stiffening quadrants and thin shrink rings. The principal elements of the magnet are shown in Fig. 1.

Besides its increased inertia, the thicker shrink ring provides a greater increase in azimuthal prestress in the coil at low temperatures. The longitudinal stiffness of the magnet is achieved by using three-point support to the 5 mm thick stainless steel helium vessel.

### *A. Design verification*

The structural integrity of this design has been checked by calculations using the finite element program CASTEM.

*Shrinking assembly* - The value chosen for shrink fit interference must be sufficient to produce the necessary prestress at 4.2 K to maintain the coil in compression over its operating range. It must not however induce too high stresses in the insulation at any temperature, the ring temperature must not exceed 120 °C at assembly to avoid softening the epoxy glass coil bandages, and the play at assembly must be sufficient to minimize the risk of the ring sticking at the wrong place.

To satisfy these constraints a maximum shrink-fit temperature difference of 60 °C has been fixed and a nominal value of 50 °C has been used for finite element calculations.

In addition, an assembly clearance of 0.3 mm on the shrink ring inner diameter of 220 mm must be provided and this corresponds to a further 60 °C temperature difference. In order to limit the temperature of the bandages to 120 °C, the magnet will therefore have to be cooled to below 0 °C for this assembly.

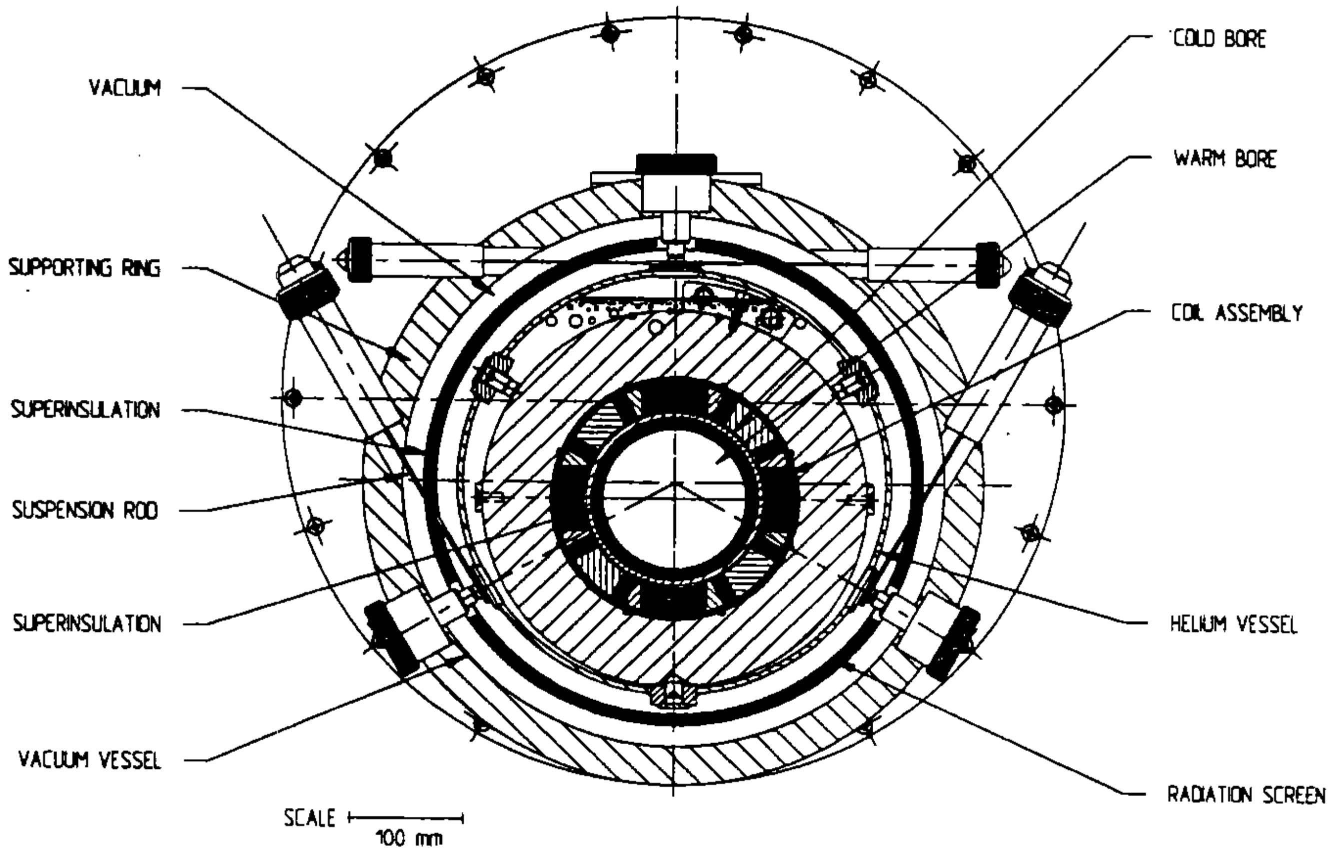


Fig. 1 Transverse cross-section.

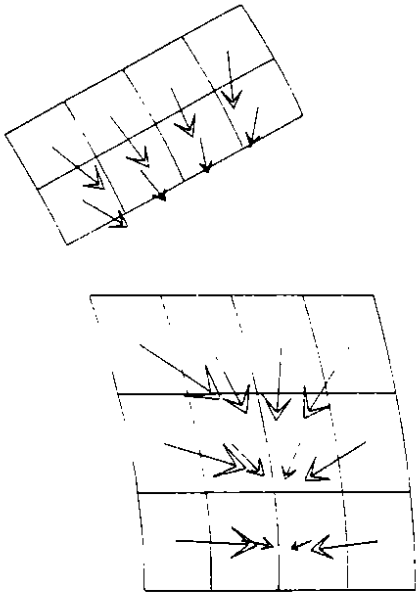

Fig. 2 Force distribution in coil.

*Cool-down* - It has been verified that during cool-down the maximum stresses in the coil vary monotonically from - 3 daN/mm$^2$ tangential and - 0.90 daN/mm$^2$ radial at room temperature to - 7 daN/mm$^2$ and - 1.5 daN/mm$^2$ respectively at 4.2 K.

*Excitation* - The force distribution on one half coil at nominal current is shown in Fig. 2. The resultant of these forces on one coil gives 67 tonne/m in the X direction and - 76 tonne/m in the Y direction. The detailed geometry is shown in Fig. 3.

Coil displacement under the influence of these forces is shown in Fig. 4. A maximum radial value of 8 μm occurring on the inner bore radius of the coil is substantially the same as that in the LEP phase 1 design.

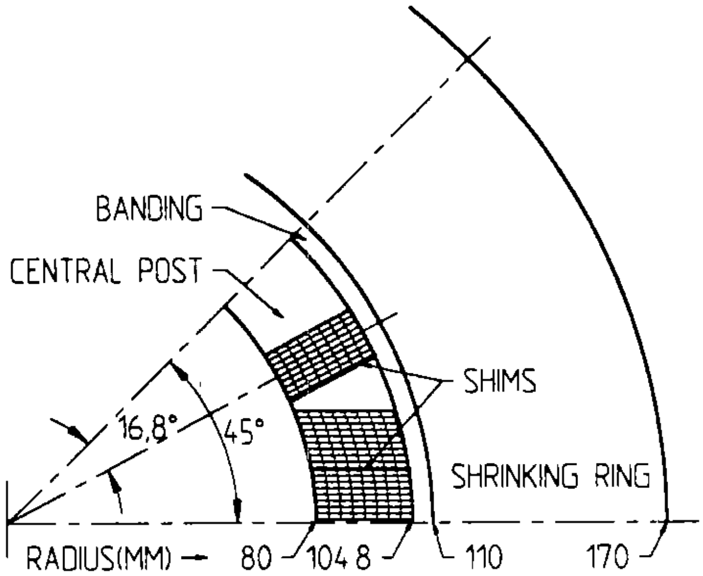


Fig. 3 Coil and support structure.

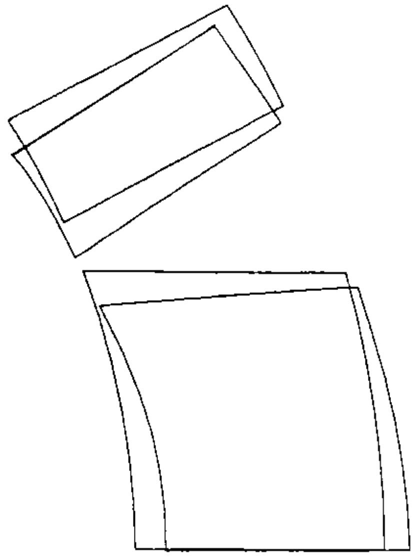

Fig. 4 Displacement due to nominal current.

*B. Prediction of quench current*

Separation of the inner coil from the centre post under magnetic loading can lead to quench in superconducting magnet structures. Using this criterion, indicated by the change from compressive to tensile of the tangential stresses at the coil/central post interface, the variation of quench current as a function of initial shrink-fit temperature difference has been determined and is shown in Fig. 5. It can be seen that in order to achieve the conductor current limit of 2300 A the structure should be assembled with an initial pre-stress given by the shrink rings having a room temperature interference fit corresponding to a temperature difference of 55 °C.

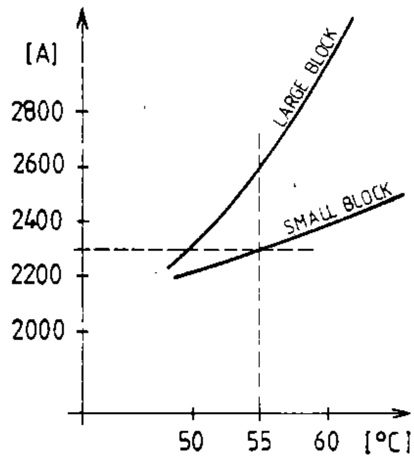


Fig. 5 Current up to which coil is in compression vs shrink fit temperature differences.

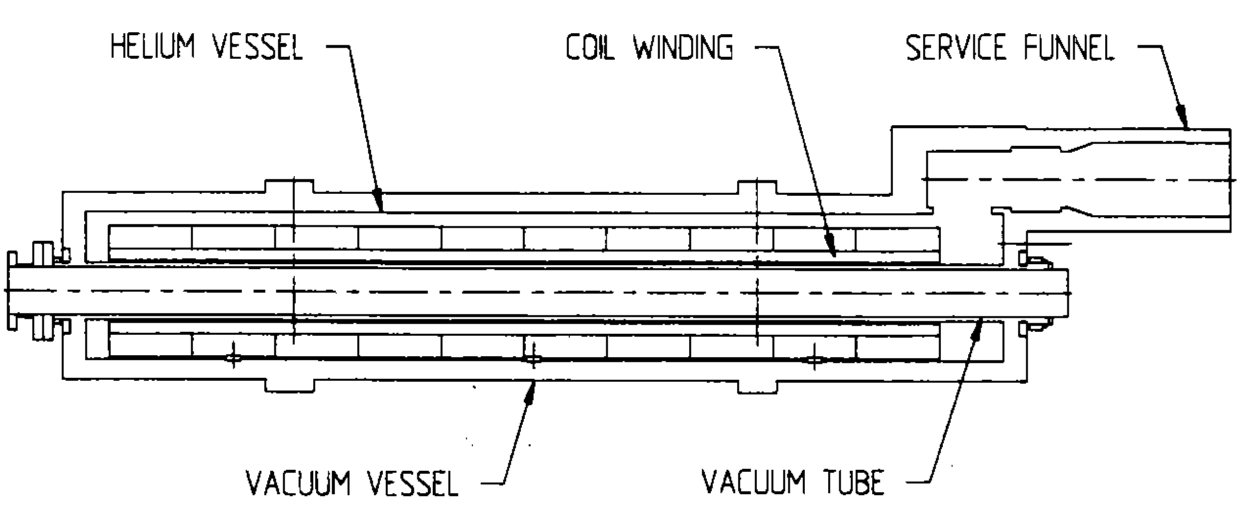


Fig. 6 Longitudinal cross-section.

### C. *Longitudinal behaviour*

Prestress is distributed along the length of the magnet by the shrink rings assembled end to end leaving a minimal inter-ring gap at room temperature.

Ten rings each 215 mm long have been chosen to compromise between ease of assembly and structural rigidity. Under these conditions, after cooling the structure to 4.2 K, the inter-ring gap becomes about 0.4 mm. Allowing for an edge radius of 1.5 mm, the maximum sagitta is then about 4% larger than would be obtained from one continuous ring.

The discontinuous nature of this structure causes stress concentrations in the coils due to bending under self-weight in the plane of each inter-ring gap. These stresses are maximum on the vertical axis and vary in inverse proportion to the effective gap width. In our case, with the magnet resting on the rigid helium vessel at three points, the maximum local stress in the coil due to this bending is increased by about 0.5 daN/mm$^2$ which is not considered to be detrimental.

## III. CRYOSTAT

The cryostat geometry can be seen in the transverse and longitudinal cross-sections of the magnet which are shown schematically in Figs 1 and 6. The differences between the new cryostat and that used for the LEP phase 1 magnets [3] concern the main helium vessel and the warm bore tube.

### A. *Helium vessel*

This has been changed from a thin corrugated structure to a 5 mm thick cylinder which serves both as an inertia support cylinder for the longitudinally more flexible magnet, and a helium jacket.

Differences in average linear thermal contraction coefficient of the magnet structure and the cryostat would cause the magnet adequately restrained at room temperature to become loose in its cryostat at 4.2 K. To maintain adequate support at 4.2 K the magnet must be pre-loaded against its restraints at room temperature. The difference in radial contraction of 0.15 mm is compensated by an initial pre-load of 200 kg at the restraints which leaves a residual pre-load of 70 kg at 4.2 K to absorb shock loads.

### B. *Warm bore*

The reduced internal coil diameter leads to a corresponding reduction in the warm bore diameter to 120 mm. Space limitations then impose that the warm bore serves both to close the vacuum vessel and as the LEP beam pipe. The bakeout temperature of 150 °C is achieved by heating the beam pipe from the ends; the conductivity of the AISI 316LN stainless steel tube is increased for this purpose by applying a 0.3 mm thick layer of electrolytic copper to its outer surface.

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