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The LHC Magnet Team reported by R. Perin

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The LHC Magnet Team
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I. INTRODUCTION

CERN is finalizing the design of a new particle accelerator-collider called the Large Hadron Collider (LHC) [1] which will enable protons and heavier particles to collide at higher energies than ever achieved before and with luminosity higher than that attained in other existing or planned facilities. For protons the head-on collision energy will reach 14 TeV with a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. Heavier ions can also be collided; e.g. for lead (Pb) ions the centre-of-mass collision energy will be up to about 1150 TeV with a luminosity of $1.8 \times 10^{27}$ cm$^{-2}$ s$^{-1}$. In addition, there will be a unique possibility of colliding high energy protons with the electrons of the Large Electron Positron Collider (LEP) at up to 1.3 TeV centre-of-mass energy.

The new machine will mainly consist of a double ring of advanced technology superconducting magnets which will be installed in the 27 km long LEP tunnel, above the LEP collider components.

As the circumference of the LHC is fixed by the LEP tunnel and the available cross-sectional space is limited, there has been from the start a quest for compact magnets, operating at the strongest possible field to reach the highest collision energy. For this reason, a 10 T quenching field was set as a target for the R & D programme of the dipole magnets [2]. This field level was considered to be an arduous, but not impossible, goal and in fact has already been reached and surpassed in model magnets.

The dimensions of single magnets operating in the range of 8 to 10 tesla exclude the possibility to install two separate magnetic rings on top of the LEP machine. This constraint has led to the development of the "twin-aperture" concept, already tested at Brookhaven National Laboratory for fields up to 5 T, leading to smaller cross-sectional dimensions and a more economical solution [2]-[4].

The LHC machine magnets will use NbTi superconductors and operate at superfluid helium temperature. The Nb3Sn superconductor route at 4.2 K, along which a model magnet was successfully built and tested [6], is still being investigated with a short dipole model under construction [7], but further development would be necessary for such an option to become technically and economically valid for the whole machine.

Benefits of using superfluid helium are its very large heat conductivity and its ability to penetrate the coils through porosities in the insulation, thus effectively cooling the conductors. This aspect is of special importance, considering that the LHC will have to operate at a beam current of nearly 1 A, and that, inevitably, some of the particles leaking out of the beam halo will be lost in the magnet coils. On the other hand, the heat capacity of all metallic parts and in particular of the superconducting cables is reduced by about a factor 10 between 4.2 and 1.9 K, with consequent higher and faster temperature rise for a given energy deposition. This, combined with the high forces, proportional to B$^2$, and the high stored electromagnetic energy, makes the magnets particularly sensitive to quasi-adiabatic heat development in the conductors, such as those originating from sudden motion, and requires extreme care in the force-retaining mechanical construction to prevent premature quenches and limit training.

A review of the requirements of the physics experiments together with a re-optimization of the machine from the points of view of beam stability, operational reliability and cost has recently led to some changes in the magnet characteristics [5]. The coil aperture has been increased from $\Phi$ 50 mm to $\Phi$ 56 mm and the magnetic length of the dipole units extended from 9 m to 13.145 m. The operational field of the main dipoles is now 8.65 T for a proton beam energy of 7.0 TeV.

The ramping time from 0.56 T (field at injection) to 8.65 T, 20 to 40 minutes [1], corresponds to a maximum rate of less than $7 \times 10^{-3}$ T/s, which is not particularly demanding with respect to magnet construction when compared to other existing superconducting accelerators.

The fundamental technical choices presented in [1]-[4] and confirmed by the results of the R & D programme are maintained and adapted to the new LHC design. A description of the magnet system is given in section III.

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II. R & D Programme

The high-field superconducting magnets are the most important and technologically the most critical components of the projected machine. For this reason, some years ago CERN has launched a R & D programme for their development in collaboration with national institutes and universities and with a vast and intense participation of industrial firms. The programme was mainly focused on the standard-cell components and particularly on the dipoles, but includes study and construction of several other magnets and items.

A. Dipoles

Descriptions and results of the dipole programme may be found in [8]-[11]. A summary of the most outstanding features and results is given below.

Superconducting cables: Twenty-four kilometres of cable for the inner coil shell made of 26, Ø 1.29 mm strands, and 42 kilometres of cable for the outer coil shell, made of 40, Ø 0.84 mm strands, have been developed and produced by the five European manufacturers and at present satisfy all main technical requirements. The process of fabrication of the wires and cables with NbTi filaments of Ø 5 µm has been optimized for high fields. The current densities in the non-copper part of the strand cross-section, taken from the finished cables at the 3 σ limit in the distribution curve of production, is 980 A/mm² at 8 T, 4.2 K, for the inner layer and 2000 A/mm² at 6 T, 4.2 K, for the outer layer. The results of the models show that the short sample quenching field of the dipole (Bsc) is close (within ~2%) to the cable short sample limit determined from strands extracted from the cables.

The total quantity produced, 14 t, is a significant amount and gives confidence that the required quality can be maintained in mass production.

Model magnets: Ten models (~ 1.3 m long) of the main dipoles (see Table I) have been made and tested.

Two magnets, identified by KEK in the table, were built in Japan by KEK in collaboration with industrial companies [12]. All other magnets were entirely built by European companies except the MTA3/CERN model which was assembled at CERN using industry made coils and other components.

The NbTi lower field model (8 TM) were designed for 8 T nominal field and had the distinctive feature of making use of 12.6 mm wide, solder-impregnated cables, which were manufactured with Ø 0.84 mm strands left over from the production for the HERA project. The behaviour of these magnets was excellent: 8.55 T at the first quench, 9 T at the third quench and cable short sample limit at 9.3 T after a few further quenches. They also showed practically no retraining after thermal cycles and half-year storage at room temperature: 8.9 T at the first quench and short sample limit at the second quench.

For the other magnets, with the exception of MTA3/CERN, the general results were the following (see Table I for details):

- At 4.2 K the maximum field of 7.9 T, corresponding to the current carrying capability of the cables as measured in short samples, was reached after one or few training quenches, confirming the soundness of the design and qualifying these magnets among the best ones for 4.2 K operation.
- At 1.8 - 2 K the ultimate field of 9.7 to 10 T was obtained but in general after a relatively large number of training quenches above 9.5 T. The analysis of the results showed that most intermediate quenches occurred at the ends, where the field is lower than in the central part, but where it is more difficult to prevent cable movements.

The most recent model, MTA3/CERN, was assembled at CERN using industry made coils basically identical to those of the previous models but wound from better performing last generation cables and with more compact ends and a support structure made with separated austenitic-steel collars and a yoke vertically split into three parts (Fig. 1).

A very high azimuthal compressive pre-stress was applied, an average 12 daN/mm² in the coil inner layer and 9 daN/mm² in the outer layer. The vertical gaps of the yoke were closed at assembly by applying a force of 2.8 MN/m by means of the stainless steel (316LN) shrinking cylinder. In those conditions the radial interference between the stainless steel collars and the yoke is 0.2 mm, and occurs over a ±230° angle around the horizontal axis. At room temperature, the design average tensile stress in the 10 mm thick shrinking cylinder should be 14 daN/mm². In the MTA3/CERN model the azimuthal stress went up to 28 daN/mm² after the longitudinal welding of the cylinder two halves. At 1.9 K, the stress reached 46 daN/mm². In order to avoid a too high compressive stress concentration at the "pole" edges of the coils at assembly, a slot has been made in the collar nose which provides sufficient elasticity for smoothing out peak stresses, while allowing the "nose" walls to maintain a pressure contact with the coils when they shrink azimuthally under the e.m. forces.

The quench history of this model is shown in Fig. 2.

At 4.3 K, the conductor short sample limit was attained at the second quench and no retraining occurred after thermal cycles.

At 2 K it had the first quench above 9 T central field, reached 9.5 T in five quenches and finally attained the record field of 10.5 T. After thermal cycles to room temperature all quenches were above 9.75 T. The conductor limit was measured by fixing the excitation at 10.5 T and gradually raising the superfluid helium temperature: quench started at 2.13 K at the first turn of the coil inner layer in the straight part, where field is at its peak value.

All other quenches started in the ends or in the splice between inner and outer layer. This makes us confident that long magnets will behave as well as short models. It is expected that these results will be confirmed by the long prototype magnets, which are now in the final assembly phase.

Since the industry is presently involved in the fabrication of seven long magnets, design optimization with models (coil ends, insulation, details of the mechanical structure, etc.) is now continuing at CERN.
A number of tests for improved cable supports in the connection (splice) and in the coil ends, by using structures of existing models. A number of tests for studying variants of mechanical structures, coil/structure interference, alternative insulation systems, etc.

**The programme is the following:**

- One model with SSC cables (MBTRA): aperture Ø 56 mm, intra-beam distance 180 mm, overall cold mass diameter 580 mm, $B_{SS} = 9.34$ T.
- One model with the same mechanical structure but cables optimized for the new design (see section III).
- A number of tests for improved cable supports in the connection (splice) and in the coil ends, by using structures of existing models.
- A number of tests for studying variants of mechanical structures, coil/structure interference, alternative insulation systems, etc.

### TABLE I

**CHARACTERISTICS OF LHC MAGNET MODELS ($L = 1.3$ m)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Aperture Ø</th>
<th>Inner Cable</th>
<th>Outer Cable</th>
<th>Collars mat.</th>
<th>$B_{SS}$ reached</th>
<th>$B_0$ reached</th>
<th>No. of quenches to pass 9 T</th>
<th>First quench field after thermal cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[mm]</td>
<td>Strand No. x Ø</td>
<td>Width [mm]</td>
<td>Strand No. x Ø</td>
<td>Width [mm]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[T]</td>
</tr>
<tr>
<td>Single aperture models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 TM1</td>
<td>50</td>
<td>30 x 0.84</td>
<td>12.6</td>
<td>30 x 0.84</td>
<td>12.6</td>
<td>Al</td>
<td>9.3</td>
<td>9.3</td>
</tr>
<tr>
<td>8 TM2</td>
<td>50</td>
<td>30 x 0.84</td>
<td>12.6</td>
<td>30 x 0.84</td>
<td>12.6</td>
<td>Al</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>MSA 1E</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al</td>
<td>9.8</td>
<td>9.7</td>
</tr>
<tr>
<td>MSA 2 KEK</td>
<td>50</td>
<td>22 x 1.39</td>
<td>15</td>
<td>37 x 0.79</td>
<td>15</td>
<td>Mn/Al</td>
<td>10.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Twin-aperture models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTA 1/E</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (S)</td>
<td>9.8</td>
<td>9.0</td>
</tr>
<tr>
<td>MTA1/A</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (C)</td>
<td>9.8</td>
<td>9.7</td>
</tr>
<tr>
<td>MTA1/H</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (C)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>MTA1/JS</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (C)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>MTA2/KEK</td>
<td>50</td>
<td>22 x 1.39</td>
<td>15</td>
<td>37 x 0.79</td>
<td>15</td>
<td>MnAl</td>
<td>10.2</td>
<td>10.5</td>
</tr>
<tr>
<td>MTA3/CERN</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>SS (S)</td>
<td>10.5</td>
<td>9.75</td>
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<tr>
<td>MBTRA</td>
<td>56</td>
<td>30 x 0.808</td>
<td>12.4</td>
<td>36 x 0.648</td>
<td>11.7</td>
<td>SS (S)</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>MFISC</td>
<td>56</td>
<td>30 x 1.10</td>
<td>16.7</td>
<td>38 x 0.87</td>
<td>16.7</td>
<td>SS (S)</td>
<td>9.9</td>
<td>9.9</td>
</tr>
</tbody>
</table>

* With industrially-made coils.

### TABLE II

**CHARACTERISTICS OF LHC TWIN-APERTURE MAGNET PROTOTYPES ($L = 10$ m)**

<table>
<thead>
<tr>
<th>Name</th>
<th>No. of units</th>
<th>Aperture Ø</th>
<th>Inner Cable</th>
<th>Outer Cable</th>
<th>Collars material</th>
<th>$B_{SS}$ reached</th>
<th>$B_0$ reached</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[mm]</td>
<td>Strand No. x Ø</td>
<td>Width [mm]</td>
<td>Strand No. x Ø</td>
<td>Width [mm]</td>
<td>[T]</td>
<td>[T]</td>
</tr>
<tr>
<td>TAP</td>
<td>1</td>
<td>75</td>
<td>24 x 0.84</td>
<td>10</td>
<td>24 x 0.84</td>
<td>10</td>
<td>Al (C)</td>
</tr>
<tr>
<td>MTP 1/A</td>
<td>3</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (C)</td>
</tr>
<tr>
<td>MTP 1/N</td>
<td>2</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (C)</td>
</tr>
<tr>
<td>MTP 2/AJS</td>
<td>1</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>Al (S)</td>
</tr>
<tr>
<td>MTP 3/EH</td>
<td>1</td>
<td>50</td>
<td>26 x 1.29</td>
<td>17</td>
<td>40 x 0.84</td>
<td>17</td>
<td>SS (S)</td>
</tr>
</tbody>
</table>

(S): Separate collars. (C): Combined collars.
Al: Aluminium alloy, SS: Austenitic steel, Mn: Mn steel.

$B_0$ = Field in the centre of the aperture.
$B_{SS}$ = Field in the aperture centre at which the conductor placed in the magnet peak field position reaches the short sample limit.

Ten-metre-long magnets: A magnet with a CERN twin structure but coils identical to those of the HERA dipole was built in industry and successfully tested at CEA-Saclay at the nominal temperature of 1.9 K [11]. This magnet, called TAP, exhibited excellent behaviour reaching the conductor short sample field at 4.2 K with no quench, and showing exactly the same properties as the single-aperture HERA magnets. When cooled down at 1.9 K, it was possible to increase the current from 6600 A to 9500 A thus reaching the conductor short sample limit of 8.3 T. It should be noted that the HERA coils have a larger aperture than the LHC coils (75 mm instead of 56 mm).
Fig. 2. Quench history of MTA3/CERN magnet

Subsequently, the construction of seven higher field (cable width 17 mm), 10 m long magnets was launched in four firms or consortia. All these magnets have the same type of coils, but three slightly different mechanical structures (Table II), as shown in their cross-sections.

The MTP1/A magnets have (Fig. 3) Al-alloy collars common to both apertures and vertically split yoke. The gap between the yoke halves is open at room temperature and closes during cooldown at about 100 K. This corresponds to the structure of the MTA1 models, but an interesting innovation has been introduced during the fabrication, i.e. gap control spacers similar to those used at LBL in a high field model magnet [13]. In the MTP1/A magnets [14] they consist of high thermal contraction (Al-alloy) bars, inserted between the yoke halves. They help obtaining the required gap with the wanted tensile pre-stress in the shrinking cylinder when the two halves of the stainless steel shrinking cylinder are welded together. At cooldown they are gradually unloaded and become completely free at liquid helium temperature. A side advantage of this solution is that they permit complete radiographic inspection of the welds.

The MTP1/N magnets have the "classical" cross-section of the MTA1 models in which the assembly clamps are maintained and not replaced by gap control spacers as in MTP1/A. The MTP2/EH magnet has the same cross-section as the last very successful MTA3/CERN model (Fig. 1), while the MTP2/AJS (Fig. 4) features separated Al-alloy collars and yoke vertically split in two parts.

The present status of manufacturing is as follows: - Several sets of coils have been made and precompressed in their collars, all mechanical components are nearing completion.

- The first fully assembled cold mass was finished in September 1993 (Fig. 5), and the magnet inserted in its cryostat should be delivered to CERN before the end of the year. This is the first of two magnets which are being supplied to CERN by INFN, Italy [14].

The magnets will be individually tested and measured. For this, a new test station with two measuring benches is being erected and will permit simultaneous testing of two
long magnets. Subsequently, four of these prototypes and one quadrupole will constitute a full half-cell (see subsection E).

Although these magnets do not yet fully incorporate the improvements already introduced in models, the experience with them will be very important for the final production.

B. Quadrupoles

Two full size quadrupole magnets of final aperture (56 mm) and length (3.5 m) have been designed and built by CEA-Saclay, using s.c. cables and structural parts made in industry. Their design and construction are described in [15].

The first one is under testing at CEA-Saclay, and will be installed in the string test.

C. Other Magnets

Combined tuning quadrupoles and octupoles: A prototype magnet of the combined tuning quadrupole ($\beta B/\beta r \pm 120$ T/m, $\pm 1600$ A, 0.8 m yoke length) and octupole corrector ($\beta^2 B/\beta r^2 \pm 10^5$ T/m$^3$, 216 A) has been built in industry. The tuning quadrupole was delivered and successfully tested in Summer 1993 [16].

Combined dipole and sextupole: A prototype 1.3 m long combined dipole ($\pm 1.5$ T, $\pm 47$ A) and sextupole ($\beta^2 B/\beta r^2 \pm 8000$ T/m$^2$, $I = \pm 458$ A) corrector was made in industry and tested successfully at RAL at 4.5 K and at CERN at 1.8 K. The magnet can be operated over the full range of specified currents with adequate margin [17].

"Spool pieces": The local sextupole and decapole correctors placed at the ends of the main dipoles are being developed by a RAL/CERN collaboration, prototypes are being built in industry [18].

Enlarged single-aperture quadrupoles for the low-B insertion: A 1.3 m long, single-aperture model quadrupole with $\phi 70$ mm aperture is being developed by a CERN/Industry collaboration [19]. Its cross-section is shown in Fig. 6.

D. Protection System

Considerable effort is devoted to study the quench protection system both for the individual magnets and the whole machine. Promising protection schemes have been worked out in parallel with the development of diodes able to absorb peak currents of 15 kA, operate at 1.9 K and withstand the radiation environment of the LHC [20].

E. The String Test

As mentioned above, one quadrupole and four dipole magnets will be installed in a large hall at CERN, after their individual test, to form one half-cell (~50 m long), which is the basic lattice and cryogenic unit of the machine. The purpose is to test the complete functional system combining cryogenics, powering and quench protection.
III. PRESENT DESIGN OF THE LHC MAGNET SYSTEM

As mentioned above in section I, a review of the requirement of physics experiments and a re-optimization of the accelerator/collider led to an increased bending length around the circumference and longer dipole magnets of slightly increased apertures operating at a lower field.

Of the 24 km of the LHC ring occupied by magnets of various types, the long arcs cover approximately 20 km of the circumference and are composed of "standard cells", a configuration which is periodically repeated 192 times around the ring (Fig. 7).

In addition to the magnets of the regular arcs, there are other magnets in the dispersion suppressor sections and on either side of each crossing point (insertion magnets).

The main features and parameters of the standard cell magnet are briefly summarized.

A. Dipoles

The design of the dipoles is made to meet the following requirements:
- Operational field: 8.65 T.
- Magnetic length: 13.145 m.
- Coil inner diameter: 56 mm.
- Distance between the axes of the apertures: 180 mm.
- Overall diameter of cold mass: ≤ 580 mm.

![Fig. 6. Cross-section of enlarged single-aperture quadrupoles for the low-β insertion](image1)

![Fig. 7. Schematic representation of a half cell](image2)

MB: Dipole magnets.
MQ: Lattice quadrupoles.
MSB: Combined sextupoles and dipole corrector.
BPM: Beam position monitor.
- o: Local Sextupole or decapole corrector.

The resulting main parameters are listed in Table III, and the corresponding cross-section is shown in Fig. 8.

The coils are formed of two winding layers made with keystoned cables (Table IV) of the same width but of different thickness, resulting from the wanted grading of current density for optimum use of the superconducting material. The copper to superconductor ratios in the strands, different in the two layers, result from stability and protection considerations. The proposed filament size allows the fabrication of superconducting wires by single stacking process. The persistent current sextupole component is $-3.56 \times 10^{-4}$ and the decapole component is $0.18 \times 10^{-4}$ for these filament diameters. These systematic error components are, however, corrected by small sextupole and decapole magnets located at each dipole end. The cables are insulated by two wraps half overlapped of polyimide tape and a wrap of b-stage epoxy impregnated fiber-glass spaced by 2 mm. Between the inner and the outer coil shells a so-called "fish-bone" spacer is placed to provide channels for circulation of the cooling helium. The insulation to ground, composed of superposed polyimide film layers, includes the quench protection heaters. A metallic sheet is inserted between insulation and collars to bridge the gaps between collars.

The force containment structure consists of the collars, the iron yoke and the shrinking cylinder which all contribute to produce the necessary azimuthal pre-compression in the coils.

The shrinking cylinder is at the same time the outer shell of the helium tank, while the inner wall forms the beam vacuum chamber. The assembly between these two cylindrical walls, the "cold mass", is kept at 1.9 K in superfluid helium at atmospheric pressure and cooled by two-phase low-pressure helium circulating in a heat exchanger tube.
installed in an axial hole of the iron yoke. In order to reduce the heat load on the cryogenic system at this very low temperature, the heat generated by the proton beams from their synchrotron radiation and the effect of beam induced currents in the resistive wall is intercepted by a shield. This is inserted within the vacuum chamber and is cooled by helium circulating at 5 to 20 K.

Main and auxiliary busbars to power the magnets of the arcs and the dispersion suppressors are located in grooves in the iron yokes. The magnet will be curved with a radius of 2700 m to match the beam paths.

### B. Lattice Main Quadrupoles

The main quadrupoles are designed to provide a 220 T/m field gradient over a magnetic length of 3.01 m, on the basis of the two-in-one configuration with Ø 56 mm coil aperture and distance between aperture axes of 180 mm. In the present powering scheme, the quadrupoles are excited in series with the dipoles, which imposes the same operation current and tracking with the dipole field. An alternative is under study to power the quadrupoles separately from the dipoles; this would make the LHC operation more flexible and suppress the need of tuning quadrupoles, but, of course, would require a larger number of high current power circuits.

The main parameter of the present design are listed in Table V. Their constructional features are very similar to that of the already built prototypes [15]. The two layer coils will be wound from the same superconducting cable in the double pancake style. This technique avoids the inter-layer splices which, being numerous in the quadrupole, would be a significant load to the cryogenic system.

### C. Insertion Magnets

There are a total of 166 special quadrupoles in the LHC insertions and straight sections differing in type, length and integrated gradient. Of this total, 114 magnets are of the lattice quadrupole type having the same cross-section but with three different lengths. The other ones are special magnets, based on a 70 mm aperture coil which is being developed for the low-beta quadrupoles [19]. In the experimental insertions, these are single aperture units, while for other insertions a two-in-one version is being designed, which may, however, operate at 4.5 K.

The low-beta quadrupoles are single-bore units 6.1 and 6.9 m long. The LHC performance depends critically on their field quality, especially on the higher order random multipole errors at low field. In order to obtain this field quality and to provide additional space for the cone of secondary particles emanating from the interaction, a novel design based on a graded coil with an aperture of 70 mm, wound from NbTi keystoned cables has been proposed. The design gradient of the magnet is 220 T/m for an excitation current of 5200 A. The design concept is presently being verified on a 1.3 m model magnet which is being developed in collaboration with an industrial firm [19] (see section II).

Other magnets in the long straight sections and insertions include beam separation/recombination dipoles, skew...
TABLE VI

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF THE CABLE FOR THE QUADRUPOLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter (mm)</td>
</tr>
<tr>
<td>Number of strands</td>
</tr>
<tr>
<td>Cable dimensions</td>
</tr>
<tr>
<td>width (mm)</td>
</tr>
<tr>
<td>thin/thick edge (mm)</td>
</tr>
<tr>
<td>Transposition pitch (mm)</td>
</tr>
<tr>
<td>Critical current at 9 T, 1.9 K (A)</td>
</tr>
</tbody>
</table>

quadrupoles, dipole correction magnets, and special dipoles for the dump insertion. Whereas most of the correcting elements are of the same design as used for the lattice, twelve of the 192 skew quadrupoles require a 70 mm aperture, as do 40 correcting dipoles. The remaining skew quadrupoles are regular tuning quadrupoles rotated through 45°.

D. Other Magnets

The strengths of all other magnets, i.e. tuning quadrupoles and octupoles, sextupoles and correction dipole, sextupole and decapole correctors spools are lower than those of the previous design for which prototypes have been successfully built and tested or are in the construction phase. Therefore the further R & D work on them will be aimed at simpler and more economical solutions.

IV. CONCLUSIONS

The first phase of the R & D programme has confirmed the soundness of the proposed technical choices for the LHC magnets:
- The 10.5 T field has been passed for the first time in an accelerator dipole and in the twin-aperture configuration foreseen for the LHC. This proves that an adequate margin with respect to the operational field can be obtained.
- It has been demonstrated both in short and long magnets that twin-aperture (two-in-one) magnets behave as well as single-aperture magnets with respect to quench/training performance.
- The superfluid helium, 1.9 K, cooling of the LHC magnets in long horizontal cryostats has been proved feasible and less difficult than expected.
- It has been verified by measurements on model magnets that the required field quality can be achieved.
- The excellent results of the last dipole model, which, after thermal cycles to room temperature, had all quenches above 9.75 T, combined with those of the long TAP prototype, demonstrate the feasibility of industrially made accelerator magnets operating at least at the field level presently foreseen for the LHC. It is expected that the long prototype magnets, which are now in the final assembly phase, will confirm this satisfactory behaviour.

The second phase of the R & D programme, already started with the construction of Ø 56 mm aperture models, will proceed with the manufacturing in industry of long prototype magnets of the new lower field design. In parallel, prototypes of the other magnets will be also built and tested.

While the first phase had been mainly aimed at obtaining the highest possible performance in terms of field levels, the second phase of the R & D programme will put more emphasis on design optimization to simplify and ease fabrication, and to ensure reliability of operation.

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REFERENCES