Preliminary views

on

8 TESLA DIPOLE MAGNET FOR THE LARGE HADRON COLLIDER

by

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Abstract

The installation of a Hadron Collider (LHC) in the LEP tunnel is considered as one of the possible alternatives for the future development of accelerator facilities at CERN. For such a Collider, bending magnetic fields in the range 8 to 10 Tesla are envisaged and some initial steps towards the design and development of 10 Tesla dipoles have been started. In parallel with that effort it is interesting to cast a first glance also at the bottom of the field range (8 T) and to see to which extent it is possible to scale from present lower field magnet designs and technologies.

One conclusion of this preliminary study is that the free space in the LEP tunnel above the LEP machine components appears to be just sufficient for the installation of two magnetically independent, vertically superposed 8 T magnets, working at super-fluid helium temperature in a common cryostat. Magnetically coupled twin bore (two-in-one) and single aperture 8 T magnets are a fortiori possible. It has also been found that the development of 8 T dipoles, of a quality suitable for the LHC, can greatly profit from technologies, tools and components that have been already developed for the HERA dipoles.

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References
1. INTRODUCTION

The installation of a Large Hadron Collider (LHC) in the LEP tunnel is considered as one of the possible next steps in the development of accelerator facilities at CERN after completion of LEP (1).

To obtain hadron beams of an energy as high as possible in the given tunnel it is necessary to use the highest possible bending magnetic field, compatibly with technical and economical feasibility of the magnets. Fields in the range 8 to 10 Tesla have been indicated as the aim to which to direct R & D on magnets. Accordingly designs of dipole models for the top of the field range (10 T) and development of suitable conductors have been started in collaboration with a number of European Laboratories (2).

In parallel with that effort, it appears reasonable to have also a first glance at the bottom of the range, i.e. at the 8 T region, where the forward step in technology, though considerable, would be less ambitious and should consequently require a more moderate effort and especially a shorter time.

With the superconducting magnets for the HERA machine (3) at DESY now going to be industrially mass-produced, it is also interesting to see which parts of their technology could be applied to eight Tesla magnets and which of their components, manufacturing tools and facilities could be used for making models, prototypes and perhaps final magnets for the Large Hadron Collider.

The present preliminary study is limited to single aperture dipoles, but most of the results could be readily applied as well to two-in-one magnets.

2. CONDUCTORS AND CURRENT DENSITY

The maximum magnetic field in the windings of an 8 T magnet can be expected to be about 8.5 T. Known critical current densities at such a field are:

<table>
<thead>
<tr>
<th>Superconductor</th>
<th>Temperature (K)</th>
<th>$J_c$ (A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>4.2</td>
<td>700 - 1000</td>
</tr>
<tr>
<td>NbTi</td>
<td>1.8</td>
<td>2000 - 2600</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>4.2</td>
<td>1700 - 2200</td>
</tr>
</tbody>
</table>

An estimate for conductors which could be industrially produced in a near future with a sufficiently small filament diameter ($\phi_{fil} \leq 10 \mu m$) is shown in fig. 1.

NbTi superconductors have at 4.2 K a too low current carrying capacity (which would lead to exceedingly thick coils and large magnet size) and are, therefore, inadequate for the construction of efficient and economical small aperture 8 T magnets. On the other hands it appears evident that in the field
range of 8 to 9 T NbTi conductors can sustain at 1.8 K a higher
current density than Nb3Sn at 4.2 K*. Other advantages of NbTi
over Nb3Sn are the present commercial availability of conductors
of the wanted characteristics (with perhaps the exception of the
desired small filament size) and the already well developed ma-
gnet fabrication techniques. These advantages may outbalance the
complication of the cryogenics at superfluid helium temperatu-
res. NbTi superconductors operating at about 2 K are, therefore,
assumed for the present preliminary study.

3. APERTURE

It is assumed that the heat from synchrotron radiation of the
hadron beams, as well as the heat from the beam induced image
currents in the walls of the beam channel will be intercepted by
a metallic shield and removed by circulating helium at 4.5 K or
slightly higher temperature (4). This shield, especially if made
or lined with high conductivity material, should be of rather ri-
gid and strong mechanical construction in order to withstand the
large electro-magnetic forces produced at magnet quenches and to
allow reasonably large spacing of supports along the magnet len-
th to limit heat conduction. Two principle designs of shields
are presented in ref. 4. With a 50 mm coil inner diameter, the
physical aperture available to the beam would be about 40 mm when
the space taken by the shield and by the main cold bore tube are
subtracted. Most of the work on LHC (1) has been made assuming a
20 mm vacuum chamber radius. It has also been shown that reducing
the coil aperture would enhance magnetic field errors and in par-
ticular persistent current effects, which would make corrections
difficult, especially if a long lattice period, favorable for
beam energy, would be preferred.

For all the above-outlined reasons a 50 mm coil inner diameter
is assumed as a basis for the present magnet design.

4. SCALING FROM THE HERA DIPOLES

The HERA dipoles have a 75 mm coil aperture and a nominal
field $B_0 = 4.65$ T at 4.6 K. An 8 T magnet operating at 2 K
and having a 50 mm coil aperture is, of course, a very diffe-
rent magnet in many respects, but it is nevertheless interes-
ting to scale its geometry from the HERA dipoles because their
techniques are now well developed and also in view of using
some of their components and manufacturing facilities for mo-
del work for reasons of time and economy.

* Note: The comparison between NbTi and Nb3Sn shown in fig.
1 might evolve in a direction more favourable to Nb3Sn, in particu-
lar for fields above 9 T, in the future, when the level of deve-
lopment of this compound would become comparable to the present
state for NbTi.
4.1 Conductor

The first question to be answered in this respect is: can the HERA dipole cable be used for the LHC 8 T magnet?

The answer, resulting from computations of magnetic field and from evaluations of achievable critical current vs. field at 2 K, is negative. The situation is shown in fig. 2 where the load line of the LHC magnet is reported against the extrapolated short sample characteristics of superconducting cables at 2 K. One finds that with too layers windings and the present HERA cable (with a minor increase of the keystoning as the only modification) a maximum field \( B_0 \) of about 7.5 T could be hardly attained.

In order to reach an 8 T field at 2 K with a reasonable operational margin with respect to short sample critical current, the following modifications to the cable are necessary:

a) An increase of the cable cross-section by about 25%, which could be obtained by the addition of 6 strands and the corresponding increase of the cable width. The LHC cable should then consist of 30 strands (0.85 mm diameter) against 24 strands in HERA.

b) The superconductor composition should be optimized for 8 T field by a probable increase of the Ti content from 46.5% (HERA) to about 49% in weight.

c) The diameter of the filaments should be reduced from 14 \( \mu m \) to, possibly, 5 \( \mu m \), in order to limit the effects of persistent currents.

d) The keystoning angle should be increased to about 2.5° in order to better match the smaller coil radius.

With the exception of point c), all required modifications are covered by present industrial technology of wire and cable production. The commercial production of wires with thin filaments (\( \leq 5 \mu m \)) and high current density demands a certain amount of development, though a number of manufacturers have already succeeded in producing experimental lengths of wires having the required characteristics. It might be, though it is not at all certain, that the finer filaments would have to be paid by a slight reduction in current density. In such an eventuality the cable cross-section would be correspondingly increased.

In the above defined LHC conductor the current density at nominal field (8 T) will be 1.6 times higher than in the HERA dipoles (4.65 T). In principle one would like to increase the amount of copper in the same proportion in order to keep the same current density in copper at quench and similar conditions of stability and protection. This would lead to a Cu/Sc ratio of 2.6:1 against 1.8:1 in HERA.
and to thicker windings. In the author's opinion, however, a 1.8:1 ratio ought to be sufficient for safe operation at 8 T.

Protection at quench must, of course, be thoroughly studied, but preliminary estimates indicate that means of fast quench propagation (e.g. heaters) have to be envisaged.

4.2 Grading of current density

Although in HERA the current density is the same in the two coil layers, in the LHC magnets it may be worth adopting a higher current density in the outer layer than in the inner one. Grading, in fact, becomes more attractive as the magnet field increases.

In the LHC 8 T magnet the peak field in the coil inner layer will be 8.5 T, while in the second layer it will be limited to only 5.8 T. It is, therefore, tempting to use a higher current density in the second layer, which, taking into account the same above-used safety margin, would reduce the cable cross-section by about 35%, i.e. to about 90% of the present HERA cable size. Of course the cable should preferably be made somewhat thinner so as to gain some turns and consequently reduce the nominal current, which in turn would lead to a re-dimensioning of the inner layer cable. This optimization process has not been carried out at this stage, but it is already possible to state that grading of current density will lead either to about 15% saving in superconductor or to a correspondingly increased margin in operation. This advantage has to be weighed against the need of a joint between the two layers (which will probably be there anyhow in 12 m long magnets) and especially against a somewhat more critical magnet protection in case of quenches in the outer layer.

4.3 Insulation

The HERA cable insulation (5), consisting of a first layer made with 0.025 mm thick Kapton tape 58% overlapped and of a second layer made with 0.12 mm thick glass fiber tape impregnated with a B-stage epoxy and wound with 3 mm gap between adjacent turns, is considered adequate for the LHC 8 T magnet. A possible modification might be the reduction of the 5 mm gap to 2 mm, in order to cope with the higher mechanical forces on the cable. The resulting porous coil construction will allow a sufficient quantity of superfluid helium in contact with the conductor to take advantage of its very high thermal conductivity.
4.4 Yoke

From magnetic field computations it was found that the inner radius and the thickness of the yoke could be kept about 10% smaller than the corresponding dimensions in the HERA dipoles. It is, however, preferable to choose at this stage the yoke dimensions exactly the same as in the HERA magnets for two reasons:

a) to open the possibility of using the HERA yoke making facilities, namely the laminations punching tools and the yoke assembly jig, for the fabrication of model and prototypes LHC magnets,

b) to maintain the possibility of going to a slightly higher field in case of future improvements of superconductor.

5. COIL CLAMPING STRUCTURE

At the central field Bo = 8 T, the electro-magnetic forces per unit area of the windings (2 layers, 30 strands cable) are a factor 2.75 larger than in the HERA dipoles at their Bo = 4.65 T nominal field. When the smaller coil aperture is taken into account, the resultant forces will be 2.3 times higher and the maximum bending moment in the coil support collars a factor 1.9 larger than in the HERA dipoles. If the same maximum stress is assumed in the collars, their width would result larger than given by the optimum coil-yoke radial distance as determined from magnet efficiency and field quality.

A different coil clamping structure is, therefore, envisaged, in which the yoke contributes in an important way. The proposed "mechanically hybrid" support structure will consist of three elements (fig.3)

- the aluminium alloy collars;
- the steel yoke, vertically split in two parts;
- a set of aluminium alloy shrinking rings, or a stainless steel cylinder, around the yoke.

The collars will be clamped around the coils at room temperature with a moderate pressure, sufficient to take the first non-linear or low-modulus coil setting and to guarantee integrity of the assembly during transport and handling. In this way any risk of room temperature flow or creep of coil components (especially of organic materials which may flow under stress at room temperature) is avoided. The dimensions of the yoke will be chosen so as to obtain the wanted gap between yoke halves, which will be determined so that:

- it will completely close during cool-down of the magnet,
- a pre-defined pressure will be exerted by the yoke on the collars at the end of the cool down,
- an adequate compression is produced at the mating faces of
the yoke halves.

The stainless steel cylinder or the aluminium alloy rings
will be shrink-fitted around the yoke, so as to exert a pre-
determined contact pressure on the yoke halves and between yoke
and collars.

During the cooling process the shrinkage of the aluminium
collars increases the pre-compression in the coils, while the
yoke halves, actuated by the stainless steel cylinders (or by the
Al rings), will move horizontally inwards applying compressive
forces to the collars-coils assembly.

At operation temperature all three components of the coil
clamping structure will collaborate in applying the necessary
prestress to the windings, while the yoke halves will be in
contact at their mating faces under a pre-determined compression
(fig. 3 b).

When the magnet is powered, the yoke mating faces will pro-
gressively unload while the compressive forces between them are
gradually replaced by part of the horizontal component of the
magnetic forces in their reaction to the tensile forces in the
shrinking rings. This process takes place with negligible displa-
cyement, due to the large rigidity of the yoke, and everything
works in practice as if the collars were resting against extreme-
ly rigid walls (fig. 3 c and d).

Coil displacement and deformation under the electro-magnetic
forces are, therefore, greatly reduced, as compared to a simple
collar clamping system, with beneficial effects on magnet sta-
bility and also on field quality.

6. MAGNET CROSS-SECTION AND FIELD

The proposed cross-section of the magnet active part is
shown in fig. 4 and its main parameters are reported in table 1.
The windings consisting of two shells are not supported inside
and behave as "roman arches" under the precompression provided by
the collars/yoke/shrinking ring assembly. Four insulated copper
spacers are inserted in each shell in order to eliminate multi-
pole field components up to the 18-pole. A flux map is presented
in fig. 5. At the nominal field Bo = 8 T the calculated maximum
field in the straight part of the windings is 8.4 T. The influ-
ence of yoke saturation on field distribution is small, as can be
seen in fig. 6. The electromagnetic forces in the coils are shown
in fig. 7.

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tr>
<td>Parameters of single aperture 8 T dipole</td>
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<tr>
<td>Nominal field</td>
</tr>
<tr>
<td>Peak field in the coils</td>
</tr>
<tr>
<td>Current density in cable</td>
</tr>
<tr>
<td>Excitation</td>
</tr>
<tr>
<td>Nominal current</td>
</tr>
</tbody>
</table>
In accordance with ref. 4, it is assumed that the magnet coils will be cooled by static helium II at 1 bar pressure. The yoke and the shrinking rings (or shrinking cylinder) will also be at 1.8 K. The outer shell of the superfluid helium containment vessel could be the shrinking cylinder itself (if this solution is adopted) or a thin stainless steel cylindrical wall tightly fitting around the shrinking rings. The quantity of He II which has an important specific heat even at those low temperatures, could, however, result too large for a reasonably short cooling down time after a quench, and it may be necessary to limit the wet region to the coil/collars assembly or even to the coils only. A thin stainless steel pipe closely fitting around the collars could then be the outer shell of the containment vessel. To further limit the wet region to the coils only, a different design would be needed for the coil/collar system. One solution could be to provide the coils with central posts and to modify accordingly the aluminium alloy collars, as sketched in fig. 8.

A schematic cross-section of the magnet in its cryostat is shown in fig. 9. whose sole purpose is to give a feeling for the dimensions needed to enclose all the cryogenic lines in the superinsulated and nitrogen cooled shield of the cryostat. For reasons of simplicity and economy, particularly for model work, all shells have been taken of circular shape, but elliptical or oval shaped shells might be considered for the final magnets. It has also to be noticed that the pumped lines for gaseous helium at 1.8 K, 16 mbar would not exist if magnetic refrigerators could be used between 4.2 K and 1.8 K. The magnet support system could be adapted from the HERA design with the addition of heat intercepts at 4.5 K.

In the final magnets the yoke can be shaped as indicated in fig. 10. This will reduce the height of the magnet by about 80 mm, and could allow the installation in the LEP tunnel of two beam channels (for p-p collisions) with magnetically independent vertically superposed magnets.

An attempt to see whether two machines with magnets in separate cryostats would fit in the available space is shown in the schematic cross-section of fig. 11, in which the cryogenic lines are placed on the magnet sides. At first sight this solution looks very difficult or impossible when considering the larger cryostat size at the ends and the need for a minimum of space for making the connections between cryostats, but a definite answer can be given only after a detailed design of the cryomagnets.
7. CONCLUSIONS

The following preliminary conclusions can be drawn:

a) A 7.5 T field could be just attained at 2 K with the present HERA cable, windings in two shells, and a new coil support structure.

b) An 8 T field with a magnet quality suitable for the LHC can be reached using a new conductor based on the HERA cable, but with the following modifications:

- Optimization of the superconducting alloy composition for 8 T field, increasing the Ti content to about 49% in weight.

- An increase of the cable cross-section by about 25% by the addition of 6 strands.

- If possible, a decrease of the filament diameter from 14 \mu m to about 5 \mu m.

All required modifications are within the reach of present industrial technology, except the last one, which will require some development.

c) Grading of current density in the two coil layers could result in 10 to 15% saving of superconductor. Such a saving, however, ought to be carefully weighed against some disadvantages.

d) Despite the different coil aperture, the magnet cross-section can be optimized in such a way that the transverse dimensions of the "iron" yoke can be kept the same as in the HERA dipoles.

Consequently, at least for model work, the following HERA dipole manufacturing tools could be used:

- the press and the other tools to mount the collars,

- the cutting tools for the "iron" laminations and the yoke assembly jig,

- parts of the collar cutting tools.

Furthermore, some components of the coil making tooling might be used by inserting suitable spacers.
e) The cryogenic system at 1.8 K is in great part new and needs considerable design and development. Cryostats and magnets have to be designed together as a whole. The requirement to keep the quantity of superfluid helium at a minimum, in order to obtain a reasonably short recooling time after a quench, may impose important constraints to the design of the coil mechanical support structure.

f) The overall cross-sectional dimensions are such that two vertically superposed, magnetically independent, 8 T magnets in a common cryostat could just fit in the space available in the LEP tunnel. This ought to be verified after a detailed study of the cryostat and of the installation procedure.

As expected, two magnetically coupled rings with "two-in-one" magnets or, of course, a single beam channel ring fit relatively easily in the available space.
ACKNOWLEDGMENTS

The information received from the Colleagues of DESY-HERA and the help in field computation by W. Hofer of LEP Magnet Group are gratefully acknowledged.

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Superconducting dipole coils for HERA.

Alternatives and improvement for superconducting dipole coils for HERA. Proceedings 8th Int. Conf. on Magnet Technology p. 255 and 259, Grenoble, Sept. 1983.


Fig. 1 Expected current density in non-copper part of superconductors suitable for the LHC magnets.
Fig. 2 Computed load line of the LHC 8 T dipole against expected short sample characteristics of superconducting cables.
FIG. 3 - Principle of "hybrid" mechanical structure.
Fig. 4 - Preliminary cross-section of active part (single aperture variant, B=8 T at 2K)
Fig. 5  Flux map at Bo = 8 T
FIG. 6: Computed variation of multipole components due to iron saturation at $R = 20\,\text{mm}$.

\[ \sum F_x = 1.32 \, \text{MN/m} \]
\[ \sum F_y = 0.68 \, \text{MN/m} \]

Fig. 7. Electromagnetic forces in the coils at $B_0 = 8\,\text{T}$
Fig. 8 - Possible assembly to limit the Helium II to the coil region only.
Fig. 9. Possible schematic cross-section of the single-aperture, 8T, 1.8K cryo-magnet. (All cryogenic lines enclosed in the cryostat.)
Fig 10: Schematic cross-section of two magnetically independent, 8T, 1.8 K magnets in a common cryostat.

(All cryogenic lines enclosed in the cryostat.)
FIG. 11. SPACE TAKEN BY TWO VERTICALLY SUPERPOSED 8T MAGNETS IN SEPARATE CRYOSTATS.