SOME ASPECTS OF TOROID AND SOLENOID DESIGN FOR LHC DETECTORS


INTRODUCTION

To establish a guide order of magnitude for design calculations it is assumed that, at LHC energies, the identification of relevant particles from their tracks requires a total magnetic bending power, perpendicular to the tracks, of around 14 Tesla meters (14Tm). It is desirable to make such a total bending power available along particle paths which are directed at all angles away from the original beams in the LHC. However as the angle between the particle path and the beams is reduced it becomes more difficult to provide the necessary bending so that an angle of around 5 degrees is regarded as a minimum which it would be desirable not to exceed.

A solenoid centred along the LHC beams would provide the required bending at angles greater than about 25 - 30 degrees. However as there is no transverse force on a particle travelling along a magnetic field line and the solenoid field lines are parallel to the beams, bending is reduced, finally to zero, as the angle is reduced to zero.

In contrast, the field lines of a toroidal field centred on and circulating around the beams are always perpendicular to the paths of particles then originating from it's axis. Also the field intensity increases inversely with radius from the beams. This means that, in principle, greater bending becomes available as the angle between the path of the emerging particle and the LHC beams, is reduced.

In practice of course the production of such a field requires windings to be placed adjacent and parallel to the beams where other items such as at least the beam pipe and the magnet cryostat are also required. The boundary at which the full field becomes available is therefore some distance radially away from the beams and low angle bending may only be achieved by placing the torus some distance along them away from the collision point.

Such considerations have led to proposals including not only solenoidal fields which increase in intensity with distance away from the central plane, so called 'magnetic bottles', but also combinations of toroids and solenoids in which a solenoid generally covers the central region around the collision point and a pair of toroids covers the ends of the solenoid.

In this paper, using particular examples, a general view of some of the construction and other technical requirements for both types of magnet is given, together with specification lists.

The example toroid magnet, with a central bore of 6m, was provided by Eggert (private communication). Such a magnet might be constructed, for instance, on the outside of a central solenoid. The forces encountered are greater than those in a toroid that would close the end of a solenoid, otherwise the problems are similar.

The main objective in the case of the solenoid was to assess the practical effectiveness of constructing a 'magnetic bottle' using a solenoid alone. The total bending requirement was met by providing a central field of 4T in a solenoid with a central plane bore of 7m.
THE TOROID

Model specification. (K Eggert)

a. Iron filled: b. Bore of field = 6m: Length = 10m
c. Outside diameter of field = 12m: d. Field at bore = 7T

Note: At 7T the iron will contribute about 2.3T and the winding therefore must produce 4.7T

With an appropriate aspect ratio a toroidal coil can be made self supporting, with the exception of the supported central leg, by winding it such that its curvature is proportional to the local magnetic field. This is not however possible with the above coil shape which must therefore be externally supported. The options are: 1. Banding, as shown in Fig.1, which leaves the magnetic aperture free of any obstruction; 2. A continuous external cylinder, discounted here because of its complete lack of radial access; 3. Ties across from the outside to inside of the coil partially obstructing the magnetic aperture.

FIGURE 1. Is a schematic, drawn roughly to scale, of the winding and the structural components required for the first option. The structural sections (modulus 200 GPa), listed in Table 1., have been calculated on the basis of an extension of 0.1%, as a suitable match to the probable maximum for the copper (modulus 120 GPa) in the superconductor. The magnitude of magnetic forces, particularly longitudinal compression in the central column, disposes towards making the complete structure cold
TABLE 1. MAGNETIC FORCES AND SUPPORT STRUCTURE

1. Central column:
   a. Outside diameter: 5.52 m
   b. Hoop compression: 26.4 MN/m
   c. Longitudinal compression: 53.3 kTonne
   d. Minimum thickness: 156 mm

2. Single coil:
   a. Minimum radius of curvature: 1.0 m
   b. Total tension: 10.4 MN
   c. Elastic extension: 0.094 %
   d. Force to central column: 9.29 kTonne

3. External banding:
   a. Maximum radius of curvature: 10.4 m
   b. Total tension: 39.4 MN
   c. Width * thickness: 550 * 358 mm * mm

4. End tensioning ring:
   a. Mean diameter: 5.5 m
   b. Hoop tension: 100 MN
   c. Length * thickness: 650 * 750 mm * mm

5. Total cold mass: 1.3 kTonne

The strain in the coil and the adjacent support structure should be matched such that there is no shear between them. Alternatively, either a very strong shear joint is required or an allowance must be made for relative motion between them. In particular such motion could generate heat locally which will cause the coil to quench.

Such a match can and has been achieved on the outer limb of the coils where they are supported by the external banding. It not possible under the banding supports at the ends but the curvature there has been adjusted to make the winding self supporting and a gap must be left as indicated. It is also not possible between the central column, which is in compression holding the end tensioning rings apart, and the winding which, as previously stated, is in tension. Allowance must therefore be made for relative movement to take place between them.

OPTION 3.

The above structure provides an unobstructed magnetic aperture. The third option, of ties spanning from inner to outer limbs of the winding, is much simpler, racetrack coils are possible, the force to the central column is reduced and, possibly of greatest significance for assembly reasons, the axial compression in it is now zero. For example, with ties at 2m intervals the required tie section diameter is 0.26m and the winding can be adequately supported between them by enclosing it in a box beam with 'flanges' 560mm wide by 74mm thick, furthermore this would reduce to 19mm with smaller ties at 1m spacing.

TABLE 2. WINDING PARAMETERS

Notes: 1. A forced flow conductor is envisaged
   2. Figures calculated for option 1., option 3. would be similar

1. Stored energy: 9.6 GJ
2. Operating current: 80 MA
3. Inductance: 3.0 H
4. Maximum dump voltage: 2.8 kV
5. Run down time: 85 Sec
6. Current density in the metal: 48 A/sqmm
7. Volume ratio of metal 70 %
8. Overall current density 34 A/sqmm
9. Conductor size over insulation 60 * 36.5 mm * mm
10. Insulation thickness 2.5 mm
11. Field in iron at centre 7.0 T
12. Field at conductor 4.7 T
13. Total current through the centre 70.5 MA
14. Number of coils 16
15. Ampere turns per coil 4.41 MA turns
16. Winding section (width * thickness) 550 * 238 mm * mm

TOROID ASSEMBLY

A major problem common to any toroid is how to place massive individual coils for fixing onto the central column. This might be achieved by straightforward horizontal loading if the toroid were to be put together with its axis vertical, the whole assembly being rotated through 90 degrees on completion. Alternatively, either the coils must be offered up at different angles, or the toroid must be rotated about its axis as the coils are loaded onto the central column.

In option 1, the individual coils must be mounted directly onto the central column and the cryostat built around the completed structure. This can in principle be achieved by constructing the coil units to include parts of both the support structure, the bands in this case, and the cryostat. Joins are then made at appropriate interfaces.

With option 3, cold support is much lighter because not only is there no banding and therefore no axial compression in the central column but also the load to the central column is reduced by the cross ties. The very real advantage is that the coils can be constructed and assembled as completely separate units.

Warm iron fills the toroid in each case. It is segmented and offered up sequentially between the coils and joined through them in a keystone structure which is self supporting against the radial magnetic forces.

SOLENOIDS

In this paper bending power is defined as the integral of the product of perpendicular field and path length to the solenoid boundary. This boundary is either the bore of the coil or an end plane. At low angles to the axis the bending power of a solenoid is limited by its length but it can be increased by increasing the field towards the ends. The main objective in this section is to examine this possibility.

Intuitively, bending power is proportional to the number of field lines crossed, from which, until an end is reached, bending power will be independent of the angle of the particle path in a solenoid where the field lines are prevented from leaking through the winding - a constant flux solenoid. Indeed this can be proved analytically in the somewhat artificial case of a uniformly tapered solenoid in which the field has somehow been held constant across the bore at any section.

This model has been used to obtain guideline limits for such solenoids and particular cases have been computed to verify the results and make the predictions more accurate. For the purposes of this exercise a
magnetic field of 7-8 Tesla is regarded as the performance limit of niobium titanium superconductor.

Taking \( Z \) as the distance along the axis from the centre of the coil, if \( B_0, R_0; B_Z, R_Z \) and \( B_r, R_r \); are the field and radius at \( Z = 0 \), \( Z \) and the half length of the coil, \( L \), respectively, then:

1. Minimum angle for full bending (phi) is \( \tan^{-1}(R_f/L) \).
2. For constant flux \( B_r R_Z = B_0 R_r \).
3. Bending power is \( B_0 R_0 \).

Then if \( B_0 R_0 = 14 \) Tm, the required coil radius and magnetic field strength at the ends of the solenoids, as a function of the half length, is given in Table 3. below:

**TABLE 3.**

<table>
<thead>
<tr>
<th>( L ) (metres)</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
</table>

With phi = 20 degrees:
- \( R_L \) (metres): 1.8 2.2 2.6 2.9 3.3 ≠ 3.6
- \( B_L \) (Tesla): 14.8 10.3 7.6* 5.8 4.6 3.7

With phi = 25 degrees:
- \( R_L \) (metres): 2.3 2.8 3.3 ≠ 3.7 4.2 4.7
- \( B_L \) (Tesla): 9.0* 6.3 4.6 3.5 2.8 2.3

Key: 1. * = NbTi performance limit. 2. ≠ = Length of straight solenoid

From the table, with phi = 20 the field limit is reached unless the solenoid is at least 7m long and a straight solenoid nearly 10m in length will do the same job. The figures at phi = 25 are 5.5m and 7.5m. It is clearly not possible to achieve the desirable angle of 5 degrees.

**COMPUTED CASES**

In the following computations the common parameters were: 1. Winding half length = 5.0m. 2. Maximum bore = 3.5m. 3. Bending power = 14Tm. A simple yoke was also included. With these parameters three different solenoids were explored, as follows:

1. A simple straight solenoid
2. A stepped solenoid with currents and geometry adjusted both for constant bending with angle and for minimum bending angle limited by a peak field of 7-8 Tesla.
3. A straight solenoid with length increased to give the same coverage as the stepped solenoid.

The comparative bending of these three solenoids is given in figure 2. below, from which it can be seen that the performance of the stepped solenoid extends to angles which are 15 degrees smaller than that of the short straight solenoid. This can however be made up by a 50% increase in length of the latter. Also the angle is reduced to 14 degrees before the bending power of either is halved.

**TABLE 4. Equivalent parameters**

<table>
<thead>
<tr>
<th>Solenoid</th>
<th>Stored energy (GJ)</th>
<th>Radius*pressure (MN/m)</th>
<th>Axial force (MN)</th>
<th>Cold mass (Tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m straight</td>
<td>2.5</td>
<td>22.4</td>
<td>75</td>
<td>280</td>
</tr>
<tr>
<td>Stepped</td>
<td>2.9</td>
<td>18 - 88</td>
<td>44 - 119</td>
<td>350</td>
</tr>
<tr>
<td>7.5m straight</td>
<td>3.7</td>
<td>22.4</td>
<td>75</td>
<td>420</td>
</tr>
</tbody>
</table>
As seen in Table 5, the computed coil is smaller than the constant flux model, probably because the field is not uniform but varies such that the lines are more perpendicular to the tracks than in the latter. However the peak field levels were not dissimilar in the two cases.

TABLE 5. Field levels
Distance from centre (m)  1  2  3  4  5
B in constant flux (T)  4.6  5.3  6.7  7.5  9.0
Peak B in step. sol. (T)  3.4  4.0  5.0  6.5  8.5

FIGURE 2. Comparative bending powers with angle.
(100% = 14%Tm)

CONCLUDING COMPARISON

Compared to the straight solenoid, the advantages and disadvantages of the stepped solenoid are as follows:

ADVANTAGES : 1. Occupies less space
               2. Stores less energy

DISADVANTAGES : 1. Higher field levels - superconductor limits
                 - higher stresses
                 2. Complex cryostat - difficult construction
                    - greater volume
                    - bore access restricted
                 3. Complex support structure

COST : The cost of the 7.5m straight solenoid will certainly be less than 50% greater than that of the similar 5m solenoid. Conversely the cost of the more complex 5m stepped solenoid will, with equal certainty, be greater than the 5m straight one. It would not therefore be particularly surprising to find that it was also greater than the 7.5m solenoid.