MAGNETIC FIELD GEOMETRIES

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The magnetic field is the easiest tool for determining the momentum of a particle through its trajectory and, the more accurate the knowledge of the magnetic field, the more accurate the particle momentum determination.
This simple fact explains why more and more particle detectors have been equipped with electro-magnets, either conventional (where the iron is magnetized by resistive coils) or superconducting (most of the magnetic field is produced by the superconducting coil, at a temperature around 4 K).
As the size of the detectors increases, with the size of the colliders, more and more of these magnets are superconducting, mainly for reducing the running cost.
This paper will recall first the various magnetic field configurations which can be used.
Then, a summary of the progress done in the construction of detector magnets since the 70's to the next collider to be put in operation in 2007, the Large Hadron Collider LHC, will be done through several examples.
Finally, a look at what can be the limitations of such magnets for the future projects will be done as conclusions.

1. The various magnetic field geometries

1.1. Why and how to use a magnetic field in a particle detector?

For a particle of charge q in a constant magnetic field B over a length L, the following relations apply:

1. Momentum p:

$$p = m\,v = q\,\rho\,B \tag{1a}$$

where m is the mass of the particle, v its velocity and ρ its bending radius

2. Deflection δ over L:

$$\delta = L/\rho \tag{1b}$$

3. Sagitta s:

$$s \sim q\,B\,L^2/8\,p \tag{1c}$$

This last equation is the basic one to determine the momentum of a particle through the sagitta of its trajectory in a known magnetic field.
Practically, three kinds of magnetic configurations have been used in detector magnets: dipoles, solenoids and toroids

1.2. Dipolar fields

In a dipole, the field is roughly uniform and perpendicular to the beam axis:

$$B_x = 0 \tag{2a}$$
$$B_y = B_0 \tag{2b}$$
$$B_z = 0 \tag{2c}$$

the direction z being the beam axis.

This field configuration gives a maximum efficiency for the particles emitted at small angles.

Practically, this field configuration can be produced either by large split-coil iron-core magnets or by saddle-shaped magnets. In both cases, there are large interaction forces between the coil and the iron.

1.3. Solenoidal fields

On the contrary, in a solenoid, the field is mainly constant along the beam axis:

$$B_x = 0 \tag{3a}$$
$$B_y = 0 \tag{3b}$$
$$B_z = B_0 \tag{3c}$$

This gives a very good momentum resolution at large angles.

Practically, this has been the most widely used structure, as it is compact and the most efficient in terms of ampere-turns.

As the years went by, a distinction was made between thick and thin solenoids. In the thin version, the amount of matter is reduced to the maximum to make as less perturbation as possible for the particles passing through the solenoid.

1.4. Toroidal field

Widely used for the fusion machines, the toroidal magnets have also been recently used for particle detectors.

They have several advantages:

1. No field along the axis.
2. The magnetic field is always transverse to the particle momentum.
3. They give the best momentum resolution at low angle.
4. There is no (or little) fringing field outside the toroid.
5. The mechanical structure is open.

But the field is very inhomogeneous and the maximum field on the coil, which is the dimensioning one for superconducting magnets, is much higher than the useful field (Fig 1).

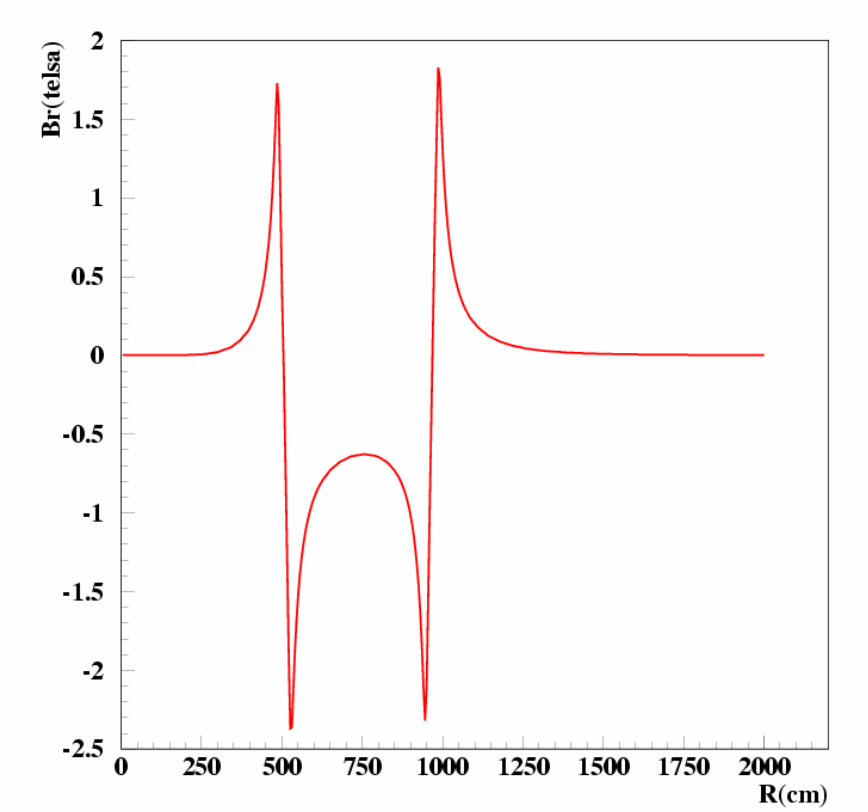

Fig 1. Radial component of the toroidal magnetic field versus the radius (from ATLAS Barrel Toroid TDR [1])

1.5. Advantages and inconveniences of each magnetic configuration

There is clearly no best solution for the kind of magnet to be used in a particle detector. For example, the three magnetic configurations previously described will be used for the LHC detectors:

1. ALICE: conventional aluminium solenoid (L3) + conventional aluminium dipole.
2. ATLAS: thin superconducting solenoid + superconducting barrel toroid + superconducting end-cap toroids.
3. CMS: superconducting solenoid.
4. LHC-b: conventional aluminium dipole.

This means that the magnet must be considered as a sub-detector and that the main design goals of the detector and the performances of the other sub-detectors must be taken into account when choosing the magnetic configuration.

2. The precursors of the 70's

The first large superconducting detector magnets appeared in the beginning of the 70's at CERN then at DESY.

We will focus our attention on four magnets, the main characteristics of which are summarized in Table 1.

The Omega magnet [2] was the first large superconducting coil to use a hollow conductor cooled by force-flow of supercritical helium, allowing a compact construction and eliminating the need for liquid helium vessels. The attraction force between the coil and the iron was supported by an array of 72 titanium struts per coil.

Table I. Main characteristics of the Omega, Pluto, Cello and TPC magnets

	OMEGA	PLUTO	CELLO	TPC
Designer (operation)	CERN (1970)	DESY (1972)	Saclay (1979)	LBL (1980)
Type	Split SC coil + iron core	SC thick solenoid	SC thin solenoid	SC thin solenoid
Field (T)	1.8	2.0	1.5	1.5
Bore diameter (m)	1.5 (gap between coils)	1.4	1.5	2.0
Length (m)	3 (pole diameter)	1.15	3.5	3.4
Stored energy (MJ)	50	4	7	11
Radiation thickness (Xo)	-	4	0.5	0.4
Remark	Hollow conductor	1st SC solenoid for colliders	Indirect cooling	Inductive coupling

The Pluto magnet [3] was the first superconducting solenoid to be installed on the electron-position Doris collider at DESY. No special attention was paid to reduce the amount of matter, but the longitudinal yoke was provided with air gaps where detector devices were installed.

The Cello magnet [4] and the TPC magnet [5] were the first two thin solenoids which were built with a thickness of less than half of a radiation length (Fig 2).

For minimizing the amount of matter in the coil and its cryostat, new techniques were used for both magnets:

1. Substitution for low mass materials (aluminium instead of copper and stainless steel).

2. Increase of the current density in the conductor (no more adiabatic stability).
3. Indirect cooling by external pipes.
4. Intrinsic protection in case of quench. If the Cello magnet used an adequate amount of high purity aluminium to stabilize the conductor, the TPC magnet developed the new concept of “quench back”, where an aluminium tube acts as a coupled secondary and drives the entire solenoid normal in a very short time in case of a quench

Fig 2. The Cello solenoid being inserted in the argon calorimeter and the iron yoke

3. The maturity period in the 80’s

3.1. Some outstanding realizations

Based on the experience gained with the previous magnets, a new generation of more ambitions projects was developed for the need of new colliders put in operation around the world, mainly Tristan at KEK, LEP at CERN and Tevatron at FNAL.

In table 2, the main characteristics of three representative magnets of this period are summarized: Topaz, Aleph and L3.

As both the dimensions and the performances of these magnets were increased, new improvements were made:
- the Topaz magnet was the first one to use the inner winding technique, i.e no more internal mandrel is used but the conductor is wound inside a reinforcing cylinder which is used to support the loop stress on the conductor when the coil is energized [6]. This technique has been widely used since.

- the Aleph magnet [7] and the Delphi magnet [8] were almost twin magnets used for almost fifteen years at LEP. They went a step further in size, in the range 5 m bore and 7 m length (Fig 3).

Table 2. Main characteristics of the Topaz, Aleph and L3 magnets

	TOPAZ	ALEPH	L3
Designer (operation)	KEK (1984)	Saclay (1987)	CERN (1987)
Type	SC thin solenoid	SC thin solenoid	Conventional dipôle. (Al. conductor)
Field (T)	1.2	1.5	0.5
Bore diameter (m)	2.7	5	11.9
Length (m)	5	6.35	11.9
Stored energy (MJ)	20	137	150
Radiation thickness (Xo)	0.7	2.0	-
Remarks	First inner winding	The largest SC magnet (with DELPHI)	The whole detector is inside the magnet. On-site assembly.

Fig 3. The Aleph solenoid alone (left) and inside the detector (right)

They both had to produce a very uniform field in the central part of the detector and so were equipped with compensating windings at the ends of the main solenoid. Both also made an extensive use of aluminium for the conductor and the cryostat.

The L3 magnet is a huge conventional dipole with an aluminium conductor. Its dimensions are such that the whole detector was included inside the magnet (Fig 4). These dimensions required special methods of construction, in particular on-site assembly [9]. It is worth noticing that after being used on the LEP collider, the L3 magnet will be used again on the ALICE experiment of the LHC collider.

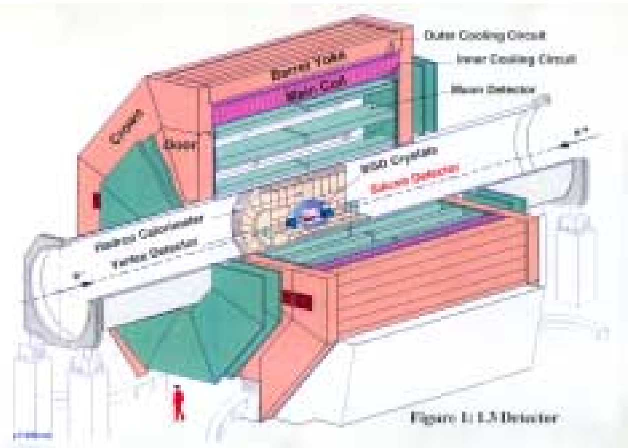

Fig 4. The L3 magnet

3.2. The SSC abortive projects

Although the construction of the SSC was stopped at an early stage, it is interesting to remember the solutions which were foreseen for the detector magnets.

Two detectors were proposed:

1. SDC: a thin central superconducting solenoid [10] and an outer conventional toroid.
2. GEM: a huge superconducting solenoid covering the whole detector [11], using a cable-in-conduit conductor and without yoke.
3. A challenging proposal was also made for a 6T thin solenoid [12].

The main characteristics of these three superconducting magnets are given in Tab 3.

Tab 3. Main characteristics of superconducting magnets designed for SSC

CHARACTERISTICS	SDC SOLENOID	GEM SOLENOID	6 T SOLENOID
Magnetic field (T)	2	0.8	6
Warm bore (m)	3.4	18	2
Length (m)	8.8	31	2.5
Stored energy (MJ)	146	3 100	155
Radiation thickness (X_0)	1.2	-	1.8

Only a prototype of the SDC solenoid was built [13]. Based on the development of high strength aluminium stabilizer, this prototype reached a ratio E/M (stored energy/effective cold mass) of 10 kJ/kg, which is still the world record. This parameter is a good criterion for scaling the lightness, compactness or efficiency of thin solenoids.

3.3. The first toroidal detector magnet

In 1995, the first toroidal detector magnet was installed at CEBAF on the CLAS experiment [14]. Built by Oxford Instrument Company, this is a 6-coil toroid, each coil being roughly 4.7 m long and 2.7 m wide. The maximum useful field is 2.0 T for a peak field on the conductor of 3.5 T, and the stored energy 18 MJ (Fig 5).

Fig 5. The CEBAF Toroid (courtesy A. Daël)

4. The present situation for LHC

The Large Hadron Collider LHC will be the largest proton-proton collider ever built. The challenge is to produce two 7-TeV proton beams which will collide in four interaction regions along the 27 km accelerator ring. First collisions are foreseen in the spring of 2007. As previously mentioned, all four experiments installed at the interaction points will use magnets. We will later focus on the two largest experiments, both using superconducting magnets, ATLAS and CMS. These two experiments have common points: they involve a very large international collaboration, the size and characteristics of the magnets they need were never realized before, industrial firms have been involved at a very early stage of the magnet component development. Besides their different magnetic configuration, the two experiments have also a different strategy for the assembly and tests. The ATLAS magnets will have only partial tests in surface (except for the central solenoid). The final assembly and full test will be done in the underground cavern. For CMS, the full magnet assembly and test will be first done in surface before transfer to the underground cavern.

4.1. The ATLAS detector

ATLAS will be the largest detector ever built for particle physics, with a length of 46 m, a width and a height of 25 m each. Its weight, 7000 t is rather low compared to the 12 500 t of the CMS detector. This is explained by its open magnetic configuration: a Central Solenoid [15] and an outer air-core toroid, consisting of the Barrel Toroid [16] and of two End-Cap Toroids [17]. The main characteristics of the different superconducting magnets which make up the detector are summarized in Table 4.

Table 4. Main characteristics of the ATLAS magnets

	CENTRAL SOLENOID	BARREL TOROID	END-CAP TOROID
Warm bore diam (m)	2.37	-	-
Inner diameter (m)	2.46	9.4	1.65
Outer diameter (m)	2.63	20.1	10.7
Axial length (m)	5.3	25.3	5
Number of coils	1	8	2 x 8
Total cold mass (t)	5.4	370	2 x 160
Rad. thickness (Xo)	0.66	-	-
Central field (T)	2	~ 1	~ 1
Peak field (T)	2.6	3.9	4.1
Current (kA)	0.76	20	20
Stored energy (GJ)	0.04	1.08	2 x 0.25

The Central Solenoid must be as thin as possible as it is placed in front of the liquid argon calorimeter. Moreover, its cryostat is common with the liquid-argon calorimeter. This solenoid was built in Japan and already tested several years ago (Fig 6).

Fig 6. The ATLAS Central Solenoid

The Barrel Toroid consists of eight coils, each having its own cryostat. This enables to install muon chambers in the magnetic field and to reach a very good momentum resolution. The assembly of the eight coils is going on and the test of the first BT coil is foreseen in spring 2004. A special test facility was built in this perspective and was previously used for the test of the B_0 coil, a BT model coil, one third in length, but full scale in width (Fig 7).

Each End-Cap Toroid is also optimized with eight coils, assembled in a single cryostat. The construction of the ECT is going on.

After the individual tests of the central solenoid and of the eight BT coils, are done in surface, all the coils will be downloaded to the underground cavern where the assembly will be done. A full electrical test of the magnet in scheduled in 2006.

Fig 7. Test of the B_0 ATLAS coil at CERN

4.2 The CMS detector

The CMS detector will include the largest solenoid ever built: central field of 4 T in a volume 12.5 m long and 6 m of inner diameter, with a stored energy of 2.7 GJ. The solenoid will consist of 5 modules connected together [18]. The winding of each module, done by the inner winding technique, consists of four layers. Two modules are already completed and the three others will be completed by the middle of 2004 (Fig. 8).

Fig 8. Blank assembly of the two first CMS modules at Ansaldo's premise (courtesy P. Fabbricatore)

These modules will be assembled at CERN in vertical position on a special platform before swivelling to horizontal position for insertion in the vacuum tank.

After the surface test foreseen in spring 2005, the magnet will be disassembled and transferred to the cavern, where it will be reassembled in order to start the physics experiment in spring 2007.

5. The limitations for the future

In this paragraph, we will only focus on solenoids.

The basic parameters for the specification of a magnet are:

1. The central magnetic field B, the length of the magnet L and its inner radius R
2. Eventually, the field homogeneity, the radiation thickness and the interaction length.

For the physicist, the relevant parameters are mainly the particle sagitta, proportional to BL^2, and the momentum resolution, proportional to BR^2.

For the magnet designer, the relevant parameters are the magnetic field on the conductor, a little bit higher than B, the mechanical forces, proportional to B^2R and the protection in case of a quench, for which the relevant parameter is proportional to $B^2R/\Delta R$, ΔR being the coil thickness.

And of course, the cost is of first importance for the resource manager.

Looking individually at each parameter does not give much information:

1. The critical magnetic field in superconducting magnets is around 10T
2. When using NbTi conductor and 20T when using Nb_3Sn
3. The maximum radius is limited to around 3.5 m when transported by truck, but can be higher with an other means of transportation (air lift) or when the assembly is done on site.
4. There is almost no limitation in length if a modular system is acceptable.

The limitations are due to the mechanical forces and the protection in case of a quench. For the mechanical forces, they must be held by the conductor and/or the external support structure. Two ways have been used:

- The homogeneous reinforcement of an aluminium conductor by micro-alloying plus cold work [19].
- A hybrid configuration as in the CMS conductor, where two sections of Al-alloy are welded to the insert containing the superconducting cable coextruded in very pure Al [20].

For the protection in case of a quench, the relevant parameter is the stored energy per unit of cold mass, the so-called ratio E/M [21]. As previously mentioned, a value of 10 kJ/kg was obtained in the SDC prototype magnet and a value of 12 kJ/kg is designed for the CMS solenoid if no energy is extracted through the dump resistor (which is not the normal operation of the magnet).

The operational E/M value can be increased by using passive (quench back tube, Al strips) or active (heaters) quench propagation system.

Taking all these points into account, a reasonable limit for the future projects can be fixed to :

1. An optimum between 3 and 4 for the ratio L/R
2. A value around 60 T^2m for B^2R
3. A limit around 15 kJ/kg for the ratio E/M, specialy for thin solenoids

6. Conclusions

Big improvements have been done in the last thirty years for the magnets installed in the particle detectors. The progress of the realization of the two large superconducting magnets under continuation for LHC shows that most of the challenges are now solved. However, only the successful test of these magnets will justify the options which were chosen, as well as their correct realization.

For the future, progress in terms of performance will probably be possible, but clearly not with the magnitude obtained during the last thirty years.

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