SUPERCONDUCTING MAGNETS FOR ACCELERATORS AND DETECTORS

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Accelerators and Superconductivity have been good companions for 40 years,. This paper is a review of the characteristics of present superconducting magnets for particle accelerators and particle detectors, in particular the ones used for High Energy Physics, emphasizing similarities and differences. Discussions on material characteristics and coil structure for accelerator magnets beyond 10 T are presented.

Keywords: A. Superconducting cables, F. Superconducting Magnets, Accelerator Magnets, Detector magnets

1 INTRODUCTION

The development of superconductors for magnet applications has received a strong boost from the High Energy Physics (HEP) community, both for detector magnets and for accelerator magnets [1]. The demand for very high current density (both J_c and $J_{c \text{ overall}}$), for fine filaments, for control of the copper content, for very compact cables with large current capability, the ability to superstabilize large cables at moderate cost, together with necessity of producing hundreds of tons of materials for large projects, have been the main motivation for the continued improvement of practical superconductors. HEP has provided so far, and still does nowadays, a unique forum where material scientists, fabrication engineers and final users, i.e. magnet designers and magnet constructors, gather together and, by sharing their knowledge and their needs, are able to accomplish real progress in the technology. In particular accelerator magnets have reached a point where, in order to go beyond the 9 T limit of the present LHC in construction at CERN [2,3,4] a serious and coordinated technological effort is needed. In particular this paper reviews the main characteristics of accelerator magnets and detector magnets in the contest of various HEP projects.

2 MAGNETS FOR HADRON COLLIDERS

The relation between the energy of the relativistic particles and the bending magnetic field in a circular collider is given by:

$$E_{\text{beam}} \cong 0.3 B_{\text{dipole}} \cdot R \quad [\text{TeV}, \text{T}, \text{km}]$$

The effective radius is between about 60% and 70% of the tunnel mean radius because of the dipole filling factor and because of the long straight parts around the collision points.

Given the above relation the demand for high field is not surprising, even if one does not forget that what is saved in tunnel length has to be compared with increased cost of the high field [5,6].

A sketch of main components of a circular ring is given in Fig. 1. The primary magnetic elements are certainly the dipoles needed to bend the beam, but one should not forget that there is a considerable number of quadrupole magnets needed for beam focusing —both in the Arcs and in the Interacting Regions- a number of sextupoles to correct chromatic errors and a huge number (almost ten times the number of the dipoles) of small low field magnets needed for higher order multipole corrections.

In this paper we will focus on magnets used for the main ring that accelerates the two counteracting beams in synchrotron mode in a few minutes. In this phase the field of the magnet is raised together with the energy increase of the beam up to the flat top where it stays in collision mode for the beam lifetime, one or two days. The flat top field is 10-20 times higher than the injection one. Therefore these magnets explore a wide dynamic range but experience a relatively moderate field ramp.

So we will not discuss the injector chain and its magnets, however it is useful to remember that for a future collider, more powerful than the present LHC, the injector has to deliver beam at some 4-5 TeV at least, therefore it must rely on superconducting magnets as well. However, the injector has to be cycled up and down in synchrotron mode many times

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in the short period allowed for beam injection into the main ring. This implies that magnets of the injector ring have to be ramped in 10-30 seconds, a very tough constraint for superconducting magnets because of the critical role of the persistent currents and intra-cable effects, see paragraph 3.3.3.

Figure 1. Scheme of the main components of a circular accelerator. Cavities give the energy to the beam and magnetic elements take care of beam guidance and focusing.

In the Table 1 the main HEP Superconducting Accelerators built or studied so far are listed.

Table 1. Main Projects of Hadron Colliders

Project (Lab)	Energy (TeV/beam)	Operating dipole field (T)	Tunnel length (km)	Status
CBA* (BNL)	0.4	5	3.8	Cancelled in 1983
Tevatron (FNAL)	0.9	4	6.3	Operated in 1987
HERA (DESY)*	0.92	5.3	6.3	Operated in 1989
SSC (Dallas)	20	6.8	87	Cancelled in 1993
RHIC (BNL)	0.1/nucleon [®]	3.4	3.8	Operated in 1999
LHC (CERN)	7	8.3	27	Operation in 2007

* last name of the early Isabelle .

operation of superconducting magnets began in 1983 at lower field.

* after upgrading in 1998 from 0.82 TeV, 4.7 T

[®] heavy ion accelerator

A sketch of the magnet cross sections is given in Fig. 2 for most of the projects listed in Table I.

DIPOLE MAGNETS

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Figure 2. Cross section of the main dipoles for some of the projects listed in Table I.

3 GENERAL CHARACTERISTICS OF DIPOLE MAGNETS

3.1 Dipole coil structure

A dipole is like a split pair of circular coils stretched along the particle trajectory in such a way that the field is generated only along the beam pipe, as shown in Fig. 3.

Figure 3. Twin dipole coils to accelerate two counteracting beams. The field is concentrated along the beam trajectories.

3.1.1 Coil shape

It can be shown [7] that current sheets having an azimuthal profile of the surface current density J_s varying like $\cos\vartheta$ generate a perfect dipole field. The same result is obtained, as pointed out as early as 1934 [8], if we have a uniform volume current density J in a coil cross section with an azimuthal profile varying like $\cos\vartheta$, as shown in Fig. 4. This configuration is the one obtained by the intersection of two cylinders carrying uniform but oppositely directed current densities. A perfect dipole field is obtained by a winding that is the intersection of two ellipses with uniform and opposite J , too, while a perfect quadrupole field is generated by the intersection of two crossed ellipses, see Fig. 4.

Figure 4. Scheme of the coil geometry to generate ideal fields. A dipole field is given by intersecting cylinders carrying uniform and opposite currents (left) and by intersecting ellipses (center), while a quadrupole field is generated by crossed ellipses (right).

For a perfect dipole with current $J \cos\vartheta$, the field scales with the current as : $B \propto J \cdot \Delta a$, where Δa is the coil thickness at midplane and J the overall current density in the winding. It can be shown that the volume of the coil increases with the coil inner radius. Since the coil aperture is determined by accelerator physics, increasing J is the only way to reduce the coil volume and the quantity of superconductor and thereby to save cost and reduce the complexity of the whole structure.

The field pattern in the cross section of a real dipole is shown in Fig. 5 for a CERN twin dipole, together with the magnetic structure. Most of the field is generated directly by the coils but the iron yoke is still important to reduce the stray field. Also it helps to reduce the operating current density by 10-15%, with consequent reduction of the problem of magnet protection in case of a quench to normal state.

Figure 5. Cross section of the first version of the LHC twin dipole with the magnetic flux lines computed for 10 T. It can be noted the coil shape, an approximation of the ideal $\cos\vartheta$. In this sketch, for clarity, only the inner layer of the coils is shown. Outside the coils are the collars (in gray) that contain the e.m. forces and the iron yoke (in very light gray) for the flux return. The parts in dark gray at the top and the bottom of the collars are iron inserts.

Figure 6. Artistic view of a complete LHC twin dipole inside the HEII cryostat, with all its main components (courtesy of V. Frigo, CERN).

3.1.2 Current density and its consequences

As remarked in the previous paragraph, J_{overall} is the dominant factor: the best intrinsic J_c does not necessarily translate into the best current density in the winding. All of the following parameters of a superconductor, in order of importance, must be taken into account for what concern current density:

1. Superconductor performance, J_c , the non-copper (superconductor), or non-stabiliser, current density. If passive materials with bad conductivity are present, like barriers, bronze, niobium matrix, reinforcing stainless steel strips, etc., the current of the wire has to be averaged over the entire cross section. This allows fair comparison between different materials and techniques and, actually is the relevant number for magnet design.
2. Capability to control the copper/non-copper (or stabiliser/non-stabiliser) ratio α within strict tolerance, in either strand or tape. Usually accelerator magnets require α in the range 1.5-2.0 with a tolerance of ± 0.05 . For future accelerator magnets, an α as low as 0.7-0.8 may be desirable, but magnet protection can become a real issue in this case.
3. Possibility to assemble the basic elements, that typically carry 100-500 A, into cables capable of 10-20 kA, minimising the eventual J_c degradation and void fraction (usually its complement, the compaction factor, is quoted). Nowadays, J_c degradation for cabling as low as 3% for Cu-NbTi cables can be attained with compaction factor (conductor cross section over the total cable cross section) around 90%. Such high compaction factor helps to avoid excessive dilution of the current density. The use of big cables is almost mandatory in order to cut down the magnet inductance. This serves to reduce the current discharge time and thereby to avoid damage to the winding in case of a quench.
4. Possibility to choose thin insulation, like polyimide tapes; if a high temperature thermal treatment has to be done, usually the insulation gets thicker increasing the overall void fraction.

In addition severe demands are added on the conductors: fine filaments, controlled inter-strands resistance, etc. These issues will be addressed in paragraph 3.3.

As previously mentioned, these magnets have high current density and high magnetic field: then the e.m. forces are huge. As example, in the LHC dipoles the peak e.m. force density on the winding is: $J \cdot B \cong 400 \text{ A/mm}^2 \cdot 10 \text{ T} = 4$

N/mm^3 . Moreover, given the basic racetrack geometry, the coils are not self-supporting, as they are in a solenoidal shape, and any force has to be contained by an external structure, thus increasing the possibility of movements of strands or cables with respect to the cases where the force are self supported. In fact in this type of magnet the struggle is between the necessity to operate as near as possible to the critical surface in order to take the maximum advantage of J_c and the necessity to operate far enough from the critical surface in order to have a reasonable quench energy to have stability against small perturbations. Usually the compromise is to work at 80-90% of the maximum current, defined as the intersection of the magnet load line with the critical current curves given by short sample measurements.

A cross section of a superconducting wire and a picture of a cable for the LHC dipoles are reported in Fig. 7. In table II the main parameters of the LHC dipoles are reported.

Figure 7. Cross section of superconducting wire for LHC (courtesy of Europa Metall, Italy) and picture of an LHC cable (from Alstom, France). This cable had different coating on of the strands resulting in a so-called zebra-pattern and was one of the first attempt to control the inter-strand resistance in the LHC project (see para 3.3.3).

Table 2. Main parameters of the LHC cables and dipoles

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	$1.6-1.7 \pm 0.03$	$1.9-2.0 \pm 0.03$
Filament diameter (μm)	7	6
Number of filaments	8800	6425
I_c (A) @ 1.9 K	$515 (\pm 4 \%) @ 10 \text{ T}$	$380 (\pm 4 \%) @ 7 \text{ T}$
J_c (A/mm^2) @ 1.9 K	$1530 @ 10 \text{ T}$	$2100 @ 7 \text{ T}$
$\mu_0 M$ (mT) @ 1.9 K, 0.5 T	30 ± 4.5	23 ± 4.5
CABLE	Type 01	Type 02
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm) @ 70 MPa	1.900 ± 0.006	1.480 ± 0.006
Keystone angle (degrees)	1.25 ± 0.05	0.90 ± 0.05
Cable I_c (A) @ 1.9 K	$13750 @ 10 \text{ T}$	$12960 @ 7 \text{ T}$
Maximum I_c cabling degradation	5 %	5 %
Interstrand resistance ($\mu\Omega$)	10-50	20-80

Nominal operating field	T	8.33
Ultimate operating field	T	9
Quench field from short sample	T	9.65
Coil aperture	mm	56
Coil thickness (two layers)	mm	30.5
Magnetic Length @1.9 K	m	14.3
Nominal operating current	A	11850
Operating temperature	K	1.9
Distance between aperture axes @1.9 K	mm	194
Cold mass outer diameter	mm	570
Overall length of cold mass	m	15.18
Mass of the magnet cold mass	t	27.5
Stored energy @ 8.3 T, both channels	MJ	7.1
Self Inductance (7.6 mH/meter)	mH	100
ΣF_x per unit length per quadrant	MN/m	1.7
Axial e.m. force	MN	0.37

3.1.3 Current Grading

Since coils are usually built with two shells and of course in the outer shell the field is considerably lower than in inner one, it is natural to take advantage of the steep increase of J_c at lower field by lessening the superconductor cross section in the cable of the outer shell. For example NbTi at 4.2 K doubles in critical current in passing from 8 T, $J_c \approx 1100 \text{ A/mm}^2$, down to 6 T, $J_c \approx 2300 \text{ A/mm}^2$. Then the cable cross section can be cut in half, but not so the copper or any other stabiliser, in order to avoid a too strong dissipation during a quench ($P_{\text{quench}} \propto J_{\text{Cu}}^2$). By grading of the current density the ampere-turns in the outer shell can be increased by 50-70% in the given area, with great advantage for field generation. For Nb₃Sn based conductor this advantage is less marked because of the less strong dependence of J_c on field.

Grading is useless for HTS materials, because of their flat J_c vs field dependence. A natural choice would be to use NbTi in the outer shell, as it is done in solenoids. Actually the attempt to substitute the inner shell of a very good NbTi dipole, D19 at LBNL, with one Nb₃Sn coil [9] did not reach the expected results. We think that, unlike the case of a solenoid, in dipoles the two shells are so strongly coupled mechanically, that the different mechanical and thermal properties of NbTi and Nb₃Sn windings do not allow proper control of coil prestress and movement restraint.

3.1.4 Coil Ends Design

Coil ends are usually a difficult design point, since each turn has to climb up around the beam tube, as shown in Fig. 3. The bend is saddle-type with a complicated 3-D shape and has been the object of various studies both for mechanical stability and for magnetic design. Usually the cable, that is keystoneed in cross section, is bent according to the principle of minimum strain energy or the minimum perimeter, see Fig. 8.

Figure 8. Top: lay out of one turn of a dipole with in evidence the saddle shape of the coil ends. (Courtesy of S. Russenschuck, CERN). Down: schematic of the actual ends of a complete inner layer (arranged in 4 coil block) of an LHC dipole (Courtesy of C. Lanza, CERN)

3.2 Mechanical Design

As already stressed, high field and very high current density lead to huge e.m. forces. The total force per unit length of an LHC dipole in a coil quadrant is near 2 MN/m with a prevalence of the horizontal component F_x with respect to vertical one.

To contain this huge force we need a strong structure which is formed by collars clamped around the coils at high pressure, see Fig. 5. High pressure is maintained by means of pin rods that lock the upper half collars to the lower half ones along the whole magnet. The collars restrain the coils in the radial direction, like a tube, but also squeeze the coils in the azimuthal direction by means of the wedge in the pole region, at 90° from the midplane. The wedge completes a *roman arch*, a structure well known for its intrinsic stability under compression. The azimuthal compression has to be at least as high as the e.m. forces: when the magnet is excited the action of the e.m. forces is — at first approximation — to release the pressure at the interface between collars and coils with no coil movement.

Collaring is a very critical operation and is done by means of large presses capable of about 20 MN/m. A typical compression on the coils of 100-120 MPa is applied, with a residual stress of 60-80 MPa when the external pressure is released. The collars are made of laminations produced by fine blanking, typically 3-5 mm thick, and are of special stainless steel with very low magnetic permeability when at cold and under stress, or strong aluminium alloy. For the LHC dipole, after a long period during which aluminum was the baseline, austenitic stainless steel was retained for the final design.

If collars are not enough to contain the whole magnetic force, the yoke has to be compressed against the coils by means of an external shrinking cylinder, usually made out of stainless steel (or Al alloys), that serves also as LHe or HEII vessel. This cylinder is fitted onto the yoke assembly by welding two half shells as long as the magnet. By means of a calibrated welding of the two shells the shrinkage can be more or less controlled. This is a very difficult operation to carry out with reliability and good repeatability and can be avoided if the collars can be made self sustained. Collars are typically 15-40 mm thick radially.

In another case very thin skin collars [9], 3-5 mm thick, are used: they are intended for locking the coils in the proper position and for coil handling. In this case almost all forces are kept by the yoke-outer cylinder structure, with the advantage of a 3-5% enhancement of the field because of the closer vicinity of the yoke to the centre.

Of course the design should take into account the non uniform spring back of the materials when the press is released, the eventual plasticity of a few points, like the pin rod holes, the effect of the differential thermal contraction of the various materials (for example between the Al and the iron there is a factor two!) and — most difficult — the role of friction at various locations.

The ends are a special region: here the roman arch is far from ideal, so the collaring is usually more gentle. The turns are kept in position by inserting end spacers, shown in fig. 8, and in some cases by local impregnation of the coil ends.

Joints between cables of different windings (top and bottom poles and, for twin dipoles, poles of the two apertures) are accommodated outside the coils but the splice between inner cable and outer of the same pole must be fitted inside the winding and must have low resistance, below 1 n Ω at high field, which may be a critical point in a mass production. A novel idea to accommodate splices outside the coils is given in fig. 9.

Figure 9. Splice between two cables, from the inner and from the outer layer. The splice is not internal but brought outside the coil, in a low field region, to improve both the resistance value and the induced current effect. The design was made for the LBNL-INFN high field quadrupole for the low- β insertions (see paragraph 4.2.4). (Courtesy of S. Caspi, LBNL).

3.3 Field Quality

To avoid beam losses or beam blow up due to particular resonances, the field must have an excellent accuracy, to the level of few ppm. The field can be analyzed in multipole components, [10], and each individual term should be known and controlled within ppm of the main term. The harmonic or multipole content is generally given in units that are 10^{-4} of the main term at a given radius, usually 2/3 of the coil radius: in fact it is worth noting that each component grows as R^{n-1} where n is the multipole order ($n=1$ is dipole, $n=2$ quadrupole, etc.). Usually it is measured up to $n=8$ (16th-pole). The importance of the higher order harmonics has become evident in recent years in the long tracking studies for the LHC.

3.3.1 Geometry and Iron Saturation Errors

Actual coils approximate the ideal $\cos\theta$ geometry, see Fig. 4 and 5, thus the allowed harmonics are intrinsically built up in the design. Indeed, for a magnet whose main order is n , the intrinsic higher order harmonics are: $n = n(2k+1)$, where $k=1,2$. In dipole, $n=1$, the first (and usually biggest) higher order harmonic is $n=3$ (sextupole), then there is $n=5$ (decapole), etc. Then there are harmonics due to fabrication errors, mainly due to mechanical tolerances of the cable and other components of the coil-collar-yoke assembly. Usually after the pre-series magnets these errors are well understood and can be corrected by improving the tooling and the assembly procedure, by refining the conductor placements according to results and by means of suitable correcting coils placed near the dipoles (spool pieces).

In superconducting magnets the yoke can get saturated at a few points, thus yielding a non desirable increase of sextupole at high field, a dangerous effect if it is overlooked.

3.3.2 Persistent Currents

Hard superconductors exhibit a hysteretic behavior. The highly pinned NbTi conductors used for accelerators have a large area magnetization cycle, i.e., when the field is decreased from flat top down to minimum at injection, the superconducting filaments have a considerable magnetic moment. Since the critical current density is huge at low field, $\approx 10 \text{ kA/mm}^2$, the persistent currents associated with this magnetization are very important and can destroy the desired field quality. Magnetization scales as

$$M \propto J_c \cdot D_{\text{eff}}$$

where D_{eff} is the effective diameter of the filaments: if filaments are touching each other or are coupled by a too thin spacing of good conductive materials, as is the case for many Nb₃Sn conductors, the effective diameter can be much larger than the geometrical one. Since, clearly we don't want to have low J_c , the only way to have acceptable, i.e., correctable, field distortions is to have fine filaments. In fig. 10 the variation of the sextupole over the entire dynamic range of a dipole is reported. The strong effect of persistent current can be noted at low field, while a smaller but still significant effect of the iron saturation appears at high field.

Figure 10. Sextupole component of the field in a powering cycle of an LHC dipole, measured in normal units, i.e., 10^{-4} of the dipole field at $2/3$ of the coil radius). The large effect of the persistent currents at injection as well as the effect of the iron saturation at high field are evidenced. (Courtesy of L. Bottura, CERN).

The situation is complicated by the fact that these persistent currents are not exactly constant during the stay at low field: they drift, by an amount that cannot be explained in terms of flux creep only, and when the magnet starts to be ramped up again they resume their initial values generating the so-called snap back effect [11].

A complicated powering cycle and a dynamic correction scheme based on a real time measurements of a few reference magnets with feedback into the sextupole correctors (and into higher order corrector magnets) are required to cure these persistent current effects. To limit these effects fine filaments are needed: 6-7 μm in the case of LHC, while 5 μm was the specification in the SSC. As mentioned in section 3., the SSC was high enough in energy to need an injector based on superconducting magnets. Since these had to be ramped up quickly, in about 50 seconds, they required filaments of 2.5 μm to avoid magnetization losses becoming important. Of course very fine filaments don't have the same J_c as the optimal 20-50 μm filaments. The use of a Nb barrier surrounding each NbTi filaments is necessary to maintain a good level of J_c and good values of the transition index, although it reduces the effective superconductor cross section. However, J_c is strongly reduced below 5-7 μm , and it falls by about 20% at 2.5 μm .

3.3.3 Coupling Currents

As mentioned in section 3.1.2, we need a large cable with a high filling factor, invariably of the Rutherford type, see Fig. 7. The strands cross each other creating a regular network of contacts, see Fig. 11. Since the winding is strongly precompressed, typically 80-100 MPa, the contact points have a low resistance. The field is perpendicular to the broad

face of most of the cable, so during ramp up and down induced currents flow in all the loops shown in Fig. 11, according to the rate of field change and to the value of inter-strand resistance with consequent:

1. heat release into the strands; apart from the additional cryogenic load, there is an increase of the conductor temperature, dangerous for stability (see paragraph 3.4)
2. degradation of the quench performance (induced currents eat up J_c margin)
3. field errors that are time dependent because so is the rate of field change.

Figure 11. Schematic of the electric network due to the strong contacts between strands in a Rutherford cable (see fig. 7) when pressed in the coils. The field is mainly perpendicular to the broad face (top view at the left), such as current is induced in every loop during the ramp. (Courtesy of A. Verweij, CERN).

To make things more difficult, there is a strong variation of previous behavior from magnet to magnet because the interstrand resistance depends strongly on the surface state of the strands and on the history of the thermal and mechanical cycles (pressure, temperature cycle to cure the insulation, collaring pressure, etc) of each magnet.

In the first generation long dipoles for LHC the variation of the interstrand resistance was 1-80 $\mu\Omega$! Of course insulation of the strands is not possible because we need current sharing among strands for stability. The cure is a controlled oxidation of the cable to provide a reliable interstrand resistance in the 15-40 $\mu\Omega$ range[12].

3.4 Stability and Quench Behavior

3.4.1 Stability Margin

A good measure, although by far not exhaustive, of how much stable a magnet is against heat releasing perturbations, is the enthalpy margin, i.e. the energy necessary to increase a unit volume of coil from bath temperature to the transition (current sharing) temperature.

$$\Delta H = \int_{T_0}^{T_c(I)} C(T) dT$$

A quench occurs when the temperature increases of :

$$\Delta T = T_c(I) - T_0$$

Values of this so-called temperature margin are 0.6 K for the SSC and 1.4 K for the LHC. It should be noted that, given the different operating temperature and since $C(T) \propto T^3$, the enthalpy margin is about the same for both magnet designs [13].

A practical rule for stability is to consider that the minimum amount of copper is about 55% in cross section for NbTi based conductor, while only 50% suffices for Nb₃Sn, and to operate the magnets at 80-85% of the maximum I_c along the load line.

3.4.2 Training

When a magnet like this, with very high current density and small amount of stabilizer, is excited in the virgin cycle it very rarely reaches the maximum current. More often a quench is induced by some movement in the coils, either strands, cables or portion of the coils, at a certain I_q or B_q much lower than the nominal maximum one. Then, after cooling the magnet down again, the ramp is repeated with — usually — better results. After few cycles the magnet does

not improve its performance anymore. The slow increase of the quench current is called training. If the plateau of performance is sensibly lower than values given by short sample measurements, the magnet is degraded.

In fig. 12 training curves are shown for a series of LHC long dipoles. Certain features can be noted, for example, sudden oscillation in the performance after having reached the plateau. This effect, called de-training is due to overheating of some coil region after a quench at high field, i.e. with large stored energy. The thermally stressed region moves and due to friction does not recover its original good position, so in the next cycle this becomes a weak zone, poorly mechanically supported, and it quenches at lower current. This effect is important in LHC magnets because they are the first magnets with enough stored energy to trigger routinely this thermally induced movement.

Magnets should have high initial quench values and good memory effect. That is, after training and warm up to room temperature, upon subsequent cool down they start near the earlier plateau with little re-training. These points are important because training is expensive and time consuming. In the LHC all 1232 dipoles will be submitted to a short training cycle, before to be installed in the tunnel, in order to debug any possible weak point. However, if the memory will not be good for almost all of them, it will not be possible to operate the accelerator, because a quench in one magnet requires to discharge energy from the other 154 magnets series connected, and it increases the temperature above T_c of the other magnets in the same cryogenic circuit. It is clear that for accelerators the demand on quench performance, and particularly on memory behavior, are much more severe than in other large scale applications of superconductivity.

Figure 12. Training curves of five LHC dipole prototypes of the old generation: 5 coil blocks design, aluminum collars (courtesy of A. Siemko, CERN). The operating field of 8.3 T and the maximum field of 9.7 T, as given by short samples measurements, are shown (horizontal dashed lines). Magnets N1 and AJ1 reached the plateau near short sample, where they showed de-training effect. The memory is very good for magnet AJ1 (almost no re-training after thermal cycle) and almost absent for A1. The magnet AJ2 was strongly degraded due to a weak point in a junctions.

Good magnets also have the plateau at the $I_{\max}$ as predicted by I_c measurements on cable short samples. The mass production may show some spread in the performance, then there is the necessity to operate not too near the short sample limit.

3.4.3 Quench Protection

The magnet must be fully protected in case of a quench:

- $T_{\max}$ in the coils should not exceed room temperature, to avoid insulation trouble.
- Thermal gradients should not be too large in order to avoid uncontrolled stresses ($\Delta T < 50-100$ K)
- Voltage should not be excessive ($V_{\max} < 0.5-1$ kV)

In the spot where the quench originated, the power is dissipated as $P = \rho_{Cu} \cdot J_{Cu}^2$. To avoid excessive heating the current is diverted to a superconducting bus bar in parallel with the magnet coils, as soon as the voltage exceeds the opening threshold of by-pass diodes that block the shunt during normal operation. The characteristic time of the current decay in the magnet is L/R , and R is very small because the quench propagation velocity along the cable is low, $v_q \approx 20$ m/s: $dR/dt \approx 10$ m Ω /s with typical LHC parameters. Then it would take too long before the dissipation in the hot spot stops, with serious consequences for the magnet safety. Adding an external dumping resistor, a scheme widely used for other

superconducting magnets, does not work because, given the extremely high J_{Cu} (current density in the stabilizer after a quench), a large resistance of about $1\ \Omega$ would be needed, with too high voltage, 10 kV or more, across the magnet terminals. The only way is to force the quench to propagate quickly and this is obtained by firing heaters, in the form of stainless strips, forcing a fraction of the winding to quench in 30-50 ms. Due to the steep increase of the resistance, the current decay is fast with a high dB/dt. This helps quench regions far from the heaters, making the resistance increase even faster. Most of the magnetic energy is dissipated in the winding but it is spread over the whole coil, so as to limit the hot spot temperature and the thermal gradients. Since the discharge resistance is all internal, the resistive voltage tends to balance the opposite inductive voltage. The cancellation is not perfect because the resistance and inductance distribution along the coil is not the same. In the LHC magnets a very reasonable $V_{max} \approx 600\text{ V}$ is obtained in normal quench discharge conditions.

4 MAGNETS BEYOND 10 T

Nb_3Sn technology is so far the only viable technology for magnets with field in excess of 10 T, even if the progress of Nb_3Al and of ceramic high T_c superconductors (HTS) may open in future alternative routes.

A few dipole magnets have been built and tested in Nb_3Sn at BNL in the period 1980-92 [14, 15], where both React and Wind (R&W) technique as well as W&R technique have been explored. The first break of the 10 T wall was reached in 1989 in a W&R Nb_3Sn dipole (with iron mirror) built by CERN-Elin (A) collaboration [16].

Then the University of Twente, NL, in collaboration with CERN designed and built a Nb_3Sn dipole that in 1995 reached more than 11 T in the CERN test stand, very near the short sample limit, evaluated about 11.5-12 T at 4.2 K, with almost no training [17]. The magnet has a single aperture of 50 mm and is 1 m long. Large persistent currents as well as coupling currents were detected, as expected since these parameters were not optimized.

A superconducting dipole, wound with Nb_3Sn cable, W&R technology, with a 4-shell coil design, with graded conductor, was designed and built by LBNL. The inner part was wound with MJR (Modified Jelly Roll) material and the outer shells with ITD (internal Tin Diffusion) material, both supplied by US companies. A 4-layer structure and the use of MJR and ITD cables were feature of the BNL dipoles referred above. The magnet, which has other unique features, like a collaring pre-stress built up with a stainless steel wire winding, was tested in spring 1997 [18] and established the record field of 13.5 T @ 1.8 K, near to the nominal critical current limit but it was plagued by a long training, that started below 11 T. The magnet showed excellent stability properties against heat deposition: to quench it at 12 T and 1.9 K it was necessary to power the heater with 20 W for more than one minute.

4.1 Nb_3Sn dipoles under construction

Two projects are under way, both aiming to have a real working magnet above 10 T at 4.2 K in one or two years with sufficient field quality and good margin to be operated safely in an accelerator. Both are still of the classical cos θ design with W&R technique.

4.1.1 Twente dipole for LHC beam separation

In the LHC there are a few special NbTi dipoles with a large single aperture, 88 mm, designed either to separate or join the two proton beams. Twente University is building, under a contract with CERN, a 1 m long dipole that should generate 10 T in such a big aperture [19]. The magnet test is foreseen by 2003 and then, if successful, it may be followed by a 7 m long dipole, to prove the reliability of the design in a full scale magnet. Then a small series of eight of these magnets would be built to replace the first generation separator dipoles. Conductor will be of the PIT type from SMI (NL).

4.1.2 Fermilab Cos θ Project

In the R&D program for the American VLHC (Very Large Hadron Collider, 50+50 TeV protons), Fermilab has designed and is starting to build dipoles with 12-12.5 T quench field, with an aperture of 43 mm bore, operating at 4.2 K [20]. The magnet, intended for an actual operating field of 11 T, has a cos θ coil lay out, probably the best and the most efficient design for field of this level. The focus of this project is on easy techniques scalable to mass production at low cost and reasonable safety margin.

For the project cables capable of $J_c = 1800\text{--}2000\text{ A/mm}^2$ at 12 T, 4.2 K in real operating conditions of 100-120 MPa transverse stress, are required. ITD, MJR and PIT are all considered. Cables with very low stabiliser content, $Cu/\text{non-Cu} < 1$, will probably be used, thus requiring a very accurate study of the magnet protection especially in view of a 10-15 m long version as prototype. In fact with the above mentioned J_c and copper content, in case of a quench the current density in the stabilizer is $J_{Cu\text{ max}} \approx 1300\text{--}1500\text{ A/mm}^2$, well beyond the safe limit of 1000 A/mm^2 .

So far few model magnets, 1 m long, have been tested, and the low performance traced back to problems not inherent to the winding techniques (poor mechanical support at the connection region or poisoning of conductor by chemical agents used in the insulation), so the team is confident to reach the goal very soon.

4.2 Novel Dipole Designs

In general when field gets higher the $\cos\theta$ structure ends with requiring very high prestress, that may go beyond the acceptability level, especially for brittle materials, like A15 or HTS compounds. In recent years the R&D focused on new structures.

4.2.1 Block Coil Dual Dipole

This is one of the first novel designs, proposed in recent years by P. McIntyre of the Texas A&M University [21]. In Fig.13 a cross section of the dipole is reported (a dual bore version is available, too). The conductor, in form of tape or rectangular cable, is bent in the easy way and the coils are subdivided into many small blocks by means of strips and ribs made of Inconel to intercept the horizontal stress. The vertical stresses are very moderate and by means of the strip/rib structure the peak horizontal stress is quite moderate, 50-70 MPa, a feature that looks very attractive for Nb_3Sn and for HTS. Coils are small, manageable and may possibly be manufactured by single tape with sufficient size and current carrying capability.

15 Tesla Dipole - optimized conductor

Figure 13. Left: cross section of the single bore version of the Coil Block Dual Dipole proposed by P. McIntyre, Texas A&M Univ. Conductor is arranged in rectangular block, instead of the usual roman arch. Right: a recent design of the coil end for such a magnet (coil opens for beam in and out).

However coil ends must be bent by a small amount in the non-easy direction to allow beam passage through the midplane. This bend is easier if the coil aperture can be kept small, some 25 mm or so. With such a gap and with certain assumptions on the conductor current density, this magnet can yield more than 16 T.

A special powering of the coils is needed, with two or three power supplies in order to maintain the field accuracy at the desired level in all the dynamic range. The current ramp is not the same for each coil group: this looks more complicated than the usual simple powering but, given the modern control technology, it is certainly feasible.

A simplified version, one single aperture, has been proposed to triple the energy of the Tevatron collider at Fermilab, up to a maximum of 3 TeV/beam.

4.2.2 Common Coil Dipole Magnet

This very special design, first proposed by BNL and now the main project also at LBNL, relies on simple race-track coils constituting the leading current of one coil aperture and the return current on the same side of the other aperture, rather than the return on the other side of the same aperture. In this way the two apertures are strongly coupled, the field at the ends have a very bad shape, the two apertures must be aligned vertically rather than horizontally but the coils are really simple and fully planar. It's the ideal design to use HTS or LTS tapes. Moreover, as typical of the window frame (rectangular block) coil layout the forces are easy to contain. The forces are mainly horizontally and very moderate

vertical prestress are required. Winding cost is low and assembly of coils becomes easy and flexible, with the possibility to change configuration easily. Therefore, this design seems excellent to carry out an R&D where many coils have to be built and tested.

With this dipole configuration, it looks like fields in the 15-20 T region [22], with an attractive 40 mm aperture, are reachable with sustainable stresses, provided that the conductor has enough current density. In Fig.14 a sketch of the magnet is shown.

This design has to solve many problems, the main ones being related to the field quality. Slanted coils are inside the main coil block, just below and above the beam tube. Other configurations are also possible to correct field errors at the ends, even if all these trimmings start to add complexity to a very simple and elegant design.

Figure 14. Cross section of the whole Common Coil Dipole Magnet. At right the coil configuration is sketched, showing the very simple shape at the ends, not crossing the beam channel. (Courtesy of R. Gupta, BNL).

4.2.3 R&W Common Coil Dipole

At Fermilab the possibility to build a Common Coil Dipole is under investigation, too. The magnet is much similar to the previous one, except that is based on React and Wind coils, trying to take full advantage of the easy bending. The distance between apertures is such that the curvature radius of the race-tracks is about 90 mm. This choice of R&W looks quite attractive for HTS tapes, especially Bi-2223 and future Y-123, which unfortunately don't yet have sufficient current carrying capability. An extensive R&D program is going on to test I_c degradation vs. bending radius of Nb_3Sn single wire and flat cables. Conductor is reacted at intermediate radius between the final winding radius and infinite radius, i.e. straight cable, in order to have half the effective maximum strain experienced by the material after last thermal treatment [23]. An artistic view of the ends of this dipole is shown in Fig. 15. A recent simplified model (so called race-track) went beyond the 70% of the maximum load line current, a results that allows some optimism in this route.

Fig. 15. Fermilab version with W&R cables, of the Common Coil Dipole Magnet. Elliptical shape of the beam pipe allows reduction of the gap.

4.2.4 Quadrupoles

Together with the beam separation dipoles under construction at Twente University, see 4.1.1, there is a possible use of very high field magnets in the inner triplet quadrupoles of the LHC low- β insertions, the magnets that squeeze the beams at the interaction point in order to have sufficient luminosity, i.e. p-p collisions in unit time and area.

A study of a Nb₃Sn quadrupole capable of 300 T/m field gradient in a coil aperture of 70 mm, an increment of 35% over the performance of the present 1.8 K NbTi low- β quadrupoles, was proposed few years ago by INFN of Milan, also in conjunction with LBNL [23,24]. The coil layout is of the classical $\cos 2\vartheta$ and is based on already available conductor of at least 1500 A/mm² with copper content of 50%. This project was stopped but this is the area where an important use of Nb₃Sn coils for LHC could be possible in the near (10 year from today) future. In fact some 16 to 32 quadrupoles, of a length of 5 meters, might be required by 2010 for possible replacements of the first generation NbTi low- β quadrupoles.

So the only Nb₃Sn quadrupole under construction is the one at CEA-Saclay to show the feasibility of this technology for accelerator magnets and to gain experience in this field [25]. By using the same tooling of the LHC arc quadrupoles, the aim is to build a Nb₃Sn quadrupole that - in the same space and magnet structure- yields 205 T/m gradient in a 56 mm aperture at 4.2 K, i.e. the same gradient in the same aperture yielded at 1.8 K by the NbTi arc quadrupoles. Due to very high heat deposition on these quadrupoles (they are very near to collision points) this may be a good advantage over NbTi. This project, for which a special insulation under patent has been developed, has been also proposed as first prototypal phase of low- β quadrupoles for the TESLA project, and it is now becoming an official part of the R&D for the LHC upgrade.

CONDUCTOR FOR FUTURE COLLIDERS

In order to be able to manufacture coils capable to generate fields beyond 15 T, an important breakthrough in the conductor performance is needed. For this reason researches on material are a priority in this field. So far the only conductors that are practically available are Nb₃Sn of the ITD or MJR routes. The renewal of the PIT technique pursued by the Twente team is also very promising. So far the bronze technique gives current density definitely too low, although it allows a full control of the copper content in a very large range of values.

In Fig. 16 is plotted the increase of J_c (non-stabilizer, i.e. $I_c/A_{\text{NbSn-CuSn-barrier}}$) in recent years for Nb₃Sn at 4.2 K and at reference field of 12 T. The continuous increase of J_c should be noted, demonstrating quite a vigorous growth more than thirty years after the first practical Nb₃Sn conductors!

Fig. 16. Best non-stabilizer critical current density recorded in the last decade for Nb₃Sn at reference point: 12 T, 4.2 K. The squares refers to PIT Powder-In-Tube technique, the diamonds to classical Internal Tube Diffusion or to Modified Jelly Roll techniques.

In Fig. 17 J_c curves vs field of Nb₃ are reported. The lower was the best in 1999 in short samples and the highest one refers to the goal that the US laboratory set up at that time for 2003: 3000 A/mm² at 12 T, 4.2 K. The intermediate curve is the J_c obtained in 2000 and today commercially available in real cables, used for small magnets. Today US

Industry is claiming 10-20% better values, i.e. 2600-2900 A/mm², so the goal that in 1999 looked very long term is actually nearer than expected, preparing the ground for magnets even beyond 15 T.

The main requirements for the conductor for such 15-18 T magnets could be summarized in the following list:

1. Minimum J_c (non-copper or non-stabiliser) of 3000 A/mm² at 12 T, 4.2 K or at higher temperature!
2. Effective diameter of the superconducting filaments below 20 μ m.
3. 20-30 kA cable.
4. Control of the stabiliser content (in the range 40-60% of total cross section)
5. Possibility to avoid coil heat treatment at high temperature (say above 250 °C). There is a lot of concern regarding technologies, like classical Nb₃Sn ITD, requiring heat treatment at 650 °C for 20 days on coil production of hundreds tons per week.
6. Low strain sensitivity. A technology allowing to use R&W with reasonable safety margin is surely a winner.

Of the previous list clearly points 1. and 2. are not easily compatible. ITD/MJR materials are the only ones capable of more than 2300 A/mm² but they have 60-100 μ m effective diameters of the filaments. This may be the main obstacle to build magnets for accelerator quality at very high field. Probably PIT materials are more suitable to reach both goals at the same time.

The problem of strain sensitivity would be solved if the high current density Nb₃Al will be available in cable with some kind of stabiliser. It may be also that reinforced Nb₃Sn wire could be a solution.

HTS materials play a critical role in this speculation. They are not so far from some requirements, at least on short samples; probably, for Bi based compounds, a use at 4.2 K will be obligatory to have enough current density. The progress of YBCO or similar compounds has to be closely monitored in order to understand if it will work at higher temperatures, to take the maximum advantage from the cost decreasing of the cryogenics and the increased stability given by the large heat capacity.

Figure 17. J_c vs field in strands (also SMI with PIT Nb₃Sn reached similar values). Also indicated is the long term goal, the curve passing through 3000 A/mm² at 12 T, 4.2 K, needed for dipole magnets beyond 15 T. See text for details.

A recent and extensive review of R&D on high field accelerator magnets and conductors can be found in [26,27]

5 Detector Magnets

Magnets are used in particle detectors for two main reasons:

1. electric charge identification
2. momentum spectrometry

It is worth noting that while the total deviation of a particle across a magnetic field is $\Delta\vartheta \propto B L$, being L the particle trajectory in the field B (here supposed uniform), the momentum resolution scales as $\Delta p/p \propto 1/BL^2$. This explains why for detectors large volumes pay off more than high fields. With fields ranging between 1-4 T (only the

LHC experiment CMS [28] has a magnet with 6 T of peak field on the coil), NbTi has been the only superconductors employed for these magnets.

Detector magnets have been the first large application of superconducting magnets and the place where the concept of cryogenic stabilization was worked out. Indeed, given the size and the large stored energy protection and stabilization are the main issue in designing these magnets. A further characteristic is that they have to be integrated in a complex object and the room for coil, its cryostat and the mechanical structure is frequently very tiny.

For the above mentioned reasons the conductor used for detector magnets has the following characteristics:

- large critical current, from 10 to 50-60 kA, to reduce inductance and to help in stress control
- large amount of stabilizer, either copper or more frequently aluminum, with Al/NbTi $\cong$ 10-20
- indirect coil cooling. Liquid helium circulates in channels welded to the mechanical structure of the coil. To improve cooling and for better compatibility with the coil material, the structure is in aluminum alloy.

5.1 Conductor

After the pioneristic time when all projects like the Argonne bubble chamber and CERN BEBC made use of pool boiling and wetted conductor, almost all detector magnets employed indirect cooling. One of the first, Cello, was built by soldering a Cu/NbTi insert into a grooved aluminum profile. Then a series of conductors were produced by coextrusion technique. By this techniques a Rutherford cable of Cu/NbTi strands is embedded in a pure aluminum matrix by passing it through an extrusion press whose main chamber is filled with high pressure aluminum. The final product is usually called conductor, reserving the name cable for the Rutherford insert.

Coextrusion of the superconducting cable with the pure aluminum has to achieve four important goals [29]:

1) To produce a conductor with the required tolerances, possibly without further rolling or skin-passing; Tolerances are not as tough as for accelerator cable but, especially for solenoids with many turns, can be of the order of 20-50 μ m. In some cases the preference is to try to get good shape directly from extrusion (Atlas toroid, CMS) , in other cases less accuracy is required to extrusion but then the final conductor is passed through rolls or a profiling die (Atlas solenoid, Cebaf toroid, Finuda solenoid).

2) To create the requested mechanical bonding between superconducting element and matrix; the bonding must sufficient to cope with the shear stress of the coils. The e.m. forces act on the Rutherford insert but are eventually transmitted to the mechanical structure through the matrix and usually bonding values above 15-20 MPa are required. Normally, values of 20-40 MPa are reached (being 40 MPa well beyond the yield strength for pure aluminum) but it should be underlined that bonding is extremely sensitive to the Rutherford cable surface conditions and to operative parameters: pre-heating of the cable, pressure in the extrusion chamber, etc.. From here there is the need of an extremely careful Q.A. plan and tooling. For ATLAS and CMS conductor, a new device, based on an ultra-sound scanner, that is able to process continuously the bonding and the centering of the insert inside the matrix, by means of imaging analysis, see Fig. 18.

Figure 18. Imaging via ultra-sound scanning of the Rutherford cable INSIDE the aluminum matrix for a full conductor unitm length. Dark blue correspond to 40 MPa and yellow/red strips to 15-20 MPa. The stripes, in this case correspond to impurities accumulated at the change of the aluminum billet in the coextrusion press (courtesy of J. Neuschwaneur, EMPA, Zurich).

3) to avoid a severe reduction of the critical current: the goal is usually to limit I_c degradation to less than 10% from virgin wire. Given 2-4% of degradation for cabling, this allows only 6-8% degradation for coextrusion. Since temperature can vary between 390 and 420 °C for a time of 30-100 s, according to the process and the speed used, one can see from Fig.19 that this goal is at the limit of present technology.

4) To preserve, as much as possible, a very good RRR of the aluminum. This can be achieved by using commercial —expensive- Aluminum 99.998%, (RRR greater than 2500 in the billet) and by carefully controlling the cleaning of the press.

A further parameter that has to be optimized, although its impact on magnet performance is less important than the above mentioned goals, is the contact resistance between cable and aluminum matrix. Indeed the bonding is given by the copper-aluminum intermetallic, typically 1-2 μm thick. Lack of the intermetallic generates a region of bad bonding, and even bad electrical contact between cable and stabilizer. But a too thick barrier of intermetallic, whose resistivity is pretty high, can increase the contact resistance above optimal values, thus reducing the stability (see later in the paper). For ATLAS/BT an intermetallic thickness of less than 3 μm assures contact resistance of less than $10^{-11}\Omega\text{m}$ at zero field, which has been proved to be largely sufficient for stability in the B0 model coil test [30].

Figure 19. Current degradation of strands of the Atlas BT cable vs. time for different temperatures. Usually in the coextrusion press the cable is heated at around 400 °C for 1-4 minutes.

Globally speaking, indirect cooling coupled with aluminum stabilized conductor is the most economic solution for large systems: for example the Atlas toroid conductor costs less than 2 /kA-m @ 5 T, 4.2 K and the cost of Atlas magnet system [31] (one of the largest and most complex superconducting magnet systems) is less than 90 M .

It is worth mentioning that for small conductor (less than 50 mm² in cross section) a new type of aluminum coextrusion has been devised, called conforming techniques. Here a single wire or a small Rutherford cable is aluminum clad by passing them through heated rolls, in such a way to form a die. The advantage here is that the process is much faster (50-200 m/min. rather than the 1-5 m/min. achieved in normal coextrusion).

In Fig. 20 a cross section of the conductor of the ATLAS toroid is reported and its main characteristic are reported in Table III.

Figure 20: Picture of the cross section of an ATLAS/BT conductor: a large Rutherford cable inside the pure aluminum matrix, 57 mm wide and 12 mm thick.

Frequently the magnet design requires that junctions between conductors be done inside the coils and in magnetic field. In this case the lack of cooling and the large current, 20 kA for LHC detectors, makes mandatory resistance of 0.1-0.5 n Ω . In ATLAS there are many of them, all done with a technique based on TIG welding the aluminum matrix, in few cases after partial removal of the aluminum itself. Even better results can be obtained if aluminum is totally removed and the strands are exposed to allow a more direct contact between the two cables. This technique has the disadvantage to be risky if the strands have been damaged or overstressed during coextrusion, a situation that has effectively happened in the past. One further problem of these junctions is that conductors are so big that in some cases the flux linked to the junction is not negligible, and the induced flux can quench the magnet, especially in ramping down. This effects usually requires short junction length, while good contact resistance calls for junction as long as possible (since a resistive barrier, the aluminum, is present). For Atlas an accurate study confirmed by experimental results has fixed the optimal length around 2.5 m [32].

TABLE III

MAIN PARAMETERS OF THE BT AND ECT CONDUCTOR OF THE ATLAS EXPERIMENT

		BT	ECT
GEOMETRY			
Dimension (bare)	mm ²	57 $\times$ 12	41 $\times$ 12
Unit length BT	m	1730	820
ELECTRICAL CHARACTERISTICS			
Operating current	A	20500	20500
Critical current @ 4.2K, 5T	A	58000	60000
Operating peak field	T	3.85	4.13
Operating temperature	K	4.8	4.7
Working point on load line (I_{op}/I_{max})		0.63	0.62
ALUMINUM STABILIZER			
Pure aluminum cross section	mm ²	628	430
RRR @ zero field, zero strain		800	600
Bonding cable-Al	MPa	20	15
STRAND AND CABLE			
$\varnothing$ NbTi filaments	μ m	50	50
$\varnothing$ strand	mm	1.25	1.3
Cu/sc ratio*		1.2	1.2
Cu RRR		90	90
Twist pitch	mm	50	50
No. of strand in cable		40 (38)	40
Cable size (indicative)	mm ²	27.9 $\times$ 2.25	24.2 $\times$ 2.42
Cable transposition pitch	mm	178(233)	178(233)

These parameters are actually different for the two companies involved in the work. In parenthesis are indicated alternative values.

* In order to keep traceability of the strands during coextrusion, few strands have a lay-out with Cu/NbTi $\cong$ 1.08

5.2 Mechanical structure

Two main structures are employed for detectors: solenoid and toroid. Most magnets are solenoids, having the advantage of a good efficiency factor: $\eta = B_{av}/B_{peak}$, where B_{av} is the average field seen by particles in their trajectories and B_{peak} is the peak field on the coil. Indeed for solenoids η is of the order of 0.6-0.9, (mainly determined by the diameter to length ratio, by the thickness of the iron return yoke and the eventual presence of iron end plates), while for toroid is of course much worse. For ATLAS Barrel Toroid, $\eta \approx 0.25$ ($B_{peak} = 3.8T$). But the toroid configuration has the advantage of field lines always perpendicular to the particle trajectories, so the choice is less obvious than it appears. Effectively, also because of a certain interest of having the whole detector without iron, to avoid multiple scattering limitation in the devices that detect the particles, the toroidal configuration is more and more considered for detectors. Of the two main detectors for the LHC accelerator, CMS employs a very large solenoid [28], while ATLAS, actually uses three large toroids (the Barrel Toroid, BT and two End Cap Toroids, ECT) and one relatively small solenoid [31].

For certain detectors the magnet is put inside the calorimetric part of the detector. In this case the solenoid (toroid are not used for such an application) must be as transparent as possible to radiation, gamma and particles, that has to be detected by the various devices outside the solenoid. Usually the goal is to reach a thickness of one radiation length or better. It is worth remarking that, historically, this was the first drive to use aluminum as main stabilizer. Then, due to its many advantages over copper and boosted by the success of the coextrusion techniques for conductor, aluminum has been used for all detector magnets build in the last fifteen years, regardless of the coil thinness requirements.

An important point to discuss is the force containment. Pure aluminum is very good for stability and protection but of course has very poor mechanical characteristics. In case of a toroid, like Atlas, the coils are kept by coil casings (each coil is fully impregnated inside its case), made of aluminum alloy for considerations of weight and for compatibility with coil thermal shrinkage (coils are dominated by aluminum properties). Coil casings are held one

against the other by a castellation or struts, see Fig. 21. Of course the lack of any self-support for toroidal coils, like for accelerator magnets, make the force and stress modeling and computing very critical.

For most of solenoids built so far the usual technique was to encapsulate the coils inside a restraining cylinder, made of aluminum alloy for reason of radiation transparency and for compatibility of thermal contraction. In this case two alternative technique have been applied with success.

- a) *Shrink fit technique.* Here the coils are inserted (either at room temperature or cooled) inside the cylinder that is kept warm, typically, around 100-150 °C, in order to have a clearance, during the coupling operation, of ~ 0.5 mm. Then, when all is at uniform temperature, the interference among the outer diameter of the coils and the inner diameter of the cylinder generate the wanted pre-stress, that can be increased at cold with suitable choice of the materials. This technique applies very well in a certain size range. If the coils are small the clearance generated by acceptable temperature difference is too small. If too big, it is difficult to have cylinder precise enough that the ovalization is smaller than the clearance. In any case there is the necessity of precise thermal models that take into account real properties of the coils (that is composite of Cu/NbTi cable, aluminum matrix and glass fibre-epoxy resin for insulation) and even plasticity. This technique has been applied successfully, for example, in the case of ZEUS inner solenoid.
- b) *Inner winding technique.* Here the coil is wound onto the cylinder from the inner side. In this case a special winding technology is necessary to push the conductor against the inner wall of the cylinder. Indeed a good contact must be assured between coils and cylinder, and actually the conductor must be wound with some negative hoop stress (i.e. under compression). If not, during cool down the coil might detach from the cylinder and the coils can suffer both from lack of cooling (cold comes from helium channels anchored to the cylinder) and from premature quench if the bonded interface between cylinder and coils goes in positive radial stress. This technique is widely used and applies very well when cylinders are larger than 2 m in diameter.

Figure 21: General structure of the ATLAS detector, one of the LHC experiments. Evidenced are the 25 m long race track coils forming the Barrel toroids, and the lateral coil of the End cap toroids. Less evidenced are, in the center, the coils of the superconducting thin solenoid. (courtesy of H. ten Kate, CERN).

For the new generation of solenoids the size and field requested are so huge, like CMS: inner diameter 6 meters, central field 4 tesla, that part of the stress must be sustained by the conductor itself. Rather than co-winding the pure aluminum conductor together with a reinforcing ribbon, CMS is successfully devising a new technique. Strong aluminum alloy profiles are e-beam welded to the pure aluminum matrix. In such a way the conductor itself can sustain most of the forces, although the necessity of a strong restraining cylinder still remains. Here is to be noted that due to the thickness of the coil (is the first time that a detector magnet is wound in four layers), accurate evaluation with detailed modeling has shown the necessity of bringing the reinforcement near each superconducting turn. In Fig. 22 a picture of the CMS conductor and of the cross section of the coils are shown.

Figure 22: Left: cross section of the reinforced conductor of the CMS magnet. The Ruthferford insert is embedded in pure aluminum matrix, 30 mm wide, to which are soldered two profiles of strong aluminum alloy AA 6082. Right: arrangement chosen for the four-layer winding, that extends both toward left and right of the figure, to avoid zones where along the radius (vertical in the picture) there is only pure aluminum. (Courtesy of P. Fabbriatore, INFN-Genova, I)

5.3 Stability and protection

Usually the amount of stabilizing material is dictated by protection rather than stability. Indeed, due to large time constant for current diffusion in the very good conductivity matrix, it can be shown that at the beginning of a transition, when the decision if a quench recovers or not is taken, only part of the matrix is really involved in the current sharing. However the two concepts are very much interlinked in these types of magnet since both processes can be considered adiabatic.

5.3.1 Stability

A solid and reliable approximate rule is to take into account just the distributed enthalpy margin, since many perturbations in detectors are of large extension. Furthermore, cooling capacity is large (supercritical helium flowing in the channel can take out from hundred of watts to tens of kW, according to the system) but there is considerable thermal resistance among the coils, where heat is generated, and the channel where is heat is eventually removed. Both consideration calls for a fairly good amount of enthalpy margin. For Atlas BT, fore example, the choice has been $\Delta H \approx 2 \text{ kJ/m}^3$, that is accomplished by a temperature margin $\Delta T \approx 6.8 - 4.8 = 2 \text{ K}$. This margin, together with the good conductivity of the matrix, can cope also with an internal joint with moderately high resistance. It is worth noticing that in enthalpy this is considerably larger than the margin usually requested in accelerator magnets.

However, sources of localized disturbance (i.e., less than the MPZ -Minimum Propagating Zone- length $\approx 1 \text{ m}$) must be considered, like:

- Crack of resin impregnation.
- Cable loose inside the matrix, with possibility of movements

For magnets of dimension up to 2-5 m, an MQE (Minimum Quench Energy) of about 1 J is usually required. For the new generation of LHC detectors, ATLAS toroid and CMS solenoid, the size is so huge that an energy of about 5 J or more has been required in the design. A 3-D study with transient effects has shown that, after I_c , the amount of stabilizer and its RRR is the most effective parameter for stability [33].

Both enthalpy margin and transient effect stability call for a large margin in I_c . Typically a detector magnet works at 35-40% of its I_c , that translates to a working point at about 60-65% of the maximum current along the load line. For Atlas BT, that will operate at 20.5 kA @4.8K, 3.8 T peak field, a cable I_c of 58 kA@4.2 K, 5 T is demanded (and in practice the conductors have a 10% higher I_c). In any case, given the margin and the fact that the conductor cross-section is dominated by the matrix, J_c is never an issues because it can be largely compensated by increase in NbTi cross section, without prejudice for the stabilizer content.

5.3.2 Protection

Protection of such a large magnets relies on two concepts: either a considerable part of energy is extracted, following a quench, which inevitably implies voltages of the order of 1 kV, or the energy is mainly deposited in the coils, with much lower voltage across the terminals. This solution is certainly preferred for large and complex system, where a short can cause also strong force unbalance with risk of destroying part of the detector, like in the case of the Atlas toroids.

In all cases, it is necessary to spread out the quench rapidly. If the energy is extracted, usually quench back effect is very beneficial. If energy is not extracted the ramp down is slower and the use of quench heater is mandatory, like in accelerators magnets. In contrast to accelerators magnets, here the quench heaters are not a delicate part of the coils but, since the quench margin is so huge, kW of power, and accurate studies to select their position are required.

Protection and stabilization impose the use of very high conductivity matrix. This is easily accomplished by using pure aluminum, as previously mentioned. It is worth noticing that the $RRR = 1000$ at zero field becomes 400 at 1 T and for higher field the Al magnetoresistivity saturates —another advantage of aluminum over copper.

A very effective technique to spread out quench, used successfully in the Atlas inner solenoid, is to bond longitudinal strips of pure aluminum over the coil ground insulation, using them as passively activated quench heaters.

Finally it is worth to conclude this overview of protection by showing a graph, see Fig.23, where most of the main solenoidal detector magnets built so far are represented in a plot of Energy/Mass vs. Energy. Of course the plots is very synthetic and it should be complemented by other information: for examples thin solenoids like ZEUS and ATLAS have many other and tighter constraints than the muon chamber magnets like Delphi, Aleph and CMS. However it shows the giant jump required by the LHC detectors.

A review of detector magnets, oriented towards giant system like the LHC detectors, can be found in [34,35].

Figure 23: Energy per unit mass (cold) for some of the main solenoidal detector magnets. Here no distinction is made between thin coils and muon chamber magnets. Also, toroid are not reported. SDC was an experiments for the ill-fated SSC accelerator (courtesy of A. Yamamoto, KEK).

6 Accelerator vs detector magnets

Without any pretension of completeness is may be useful to underline some similarities and differences among the magnets and the style itself of design and approach in the community of accelerators and detectors. The following tables helps to synthetize the characteristics.

TABLE IV
COMPARISON OF MAIN CHARACTERISTICS OF ACCELERATOR AND DETECTOR MAGNETS

Quality/parameter	Accelerators	Detectors
Present field range (tesla)	3 — 9	1 — 4
R&D for upgrade/future installation	Continuous (aiming 12-15 T)	None
Size (cross section $\times$ length)	1 m $\times$ 10-15 m	1-20 m $\times$ 3-25 m
Field accuracy (or knowledge)	Extreme (few 10^{-5}) near coils	0.5-5%
Superconductor quality	Extremely homogeneous Fine filaments No filamentation No bridging Strict control of Cu/NbTi Mass production	Must withstand $400\text{ }^{\circ}\text{C} \times 5\text{ min}$ Important production
Cable/conductor properties	Very compact cabling ($\approx 90\%$) Cabling degradation $< 5\%$ Size controlled better than $10\text{ }\mu\text{m}$ Inter-strand resistance controlled	Degradation (extrusion) $< 10\%$ Size controlled to $50\text{-}150\text{ }\mu\text{m}$ Cable-matrix bond $> 15\text{ MPa}$ Extrusion is a risky operation
Winding	Coils not self-supporting Winding difficult	Coils self supporting for solenoid Coils not self-supporting for toroids Winding easy (not for alloyed cond.)
Stability: MQE order of magnitude	1 mJ	1 J
Stability concept	Wet coil Little stabilizing Cu ($< 2:1$) Avoid movements by clamping	Impregnated coil large pure Al X-sect (Al:Sc $\approx 15:1$) Large T margin,
Operating point on load line	80-90%	50-65%
$J_{\text{stabilizer}}$ after quench (A/mm^2)	300-1000	30-50
Intervention time after quench	10-50 ms	0.2-2 s
Magnet protection	Quench heaters very near to coils By-pass diodes	Extraction of energy + passive QH or no extraction with strong QH
Number per installation	100-1000	Unique
Modelling and prototyping	many	Typically 1 (sometimes none)
Interaction with other systems	Weak (except in few points)	Strong

7 Conclusions

Accelerators and their experiments require very challenging magnets and have always been a strong motivator in applied superconductivity. With the LHC and its main detectors, ATLAS and CMS, a new step in size and difficulty is being faced. Moreover, magnets beyond 10 T are already under study to build a future multi-TeV collider, while detectors are expected to grow further in size.

A strong program for R&D is under way in the US under the VLHC and MUON-C programs, while in Europe the LHC is of focus of all accelerator laboratories, draining most of the resources. The development of high performing conductors, both of LTS and HTS materials, is certainly a key point of this technology and has to be supported with long terms programs. For accelerators high J_c (overall) and capability to keep under control coupling effects are the key issue, while for detector the stress-resistance and superstabilization are certainly the drive.

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