Accelerators and Superconductivity: LHC and Near Future in Europe

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Abstract— Superconductivity and accelerators have mutually benefited of tight liaisons for more than 30 years. For the Large Hadron Collider, whose construction is finished and that is under commissioning at CERN in the Geneva area, some 1750 main superconducting magnets and about 8000 superconducting corrector magnets have been manufactured, cold tested and installed in the underground tunnel. Also the giant superconducting magnets for the LHC experiments, ATLAS and CMS, have been manufactured and tested in the final assembly. The paper reviews the goal of particle accelerators and the reason of success of superconducting technologies in accelerators. It underlines the main features of accelerator magnets and discusses in detail the characteristics of the LHC magnets. The trends in development of accelerator magnets, both for applications (medicine) and for future research projects (FAIR, CERN injector upgrade) are presented.

Index Terms— Accelerators and detector magnets, accelerators, large-scale superconductivity, LHC, Nb-Ti superconductors

I. INTRODUCTION

Accelerators and superconductivity (SC) have been good companions for many years[1–5]. Starting from the Argonne bubble chamber [6,7] which was the first large superconducting magnet to be operated for Physics experiments and from the Tevatron [8,9], which was the first large accelerator based on superconductivity, high energy physics (HEP) has given a tremendous push to practical development of large-scale superconductivity applications and suitable conductors. In particular in the '80s, when the possibility of practical and economical application of SC was fading for the power sector, HEP nurtured improvements as there was a series of projects requiring continuous R&D.

The Large Hadron Collider [10], near completion at CERN, is the last of a series of large size accelerators based on SC technology, and it has a size four times and field level more than twice that of previous HEP accelerators [9],[11],[12]. Also its main detectors, named ATLAS [13] and CMS [14] are based on SC magnets of size and energy never before attained. In total, at the LHC some 15 GJ of magnetic energy will be stored in superconducting magnets. LHC is also the first large scale application of high-temperature superconductors (HTS) in an operating large device, by using 1180 currents leads of various amperage, up to 13 kA, all based on Bi-2223 [15].

Even prior to LHC, HEP experiments have increasingly required larger and more powerful magnets for momentum spectrometry, invariably manufactured using indirectly cooled, super-

stabilized conductors based on pure aluminum co-extruded NbTi cables. The super-magnets for the LHC experiments, the 25 m long ATLAS toroid and the 2.4 GJ stored energy CMS solenoid have a few features that were foreseen for other less fortunate projects, like large the superconducting magnetic energy storage (SMES) or magnetohydrodynamic (MHD) generators.

Superconductivity turned out to be essential not only for the large accelerators needed for HEP: it is becoming a critical technology also for other accelerators used for nuclear physics and for medicine. In the eighties, first generations of superconducting cyclotrons were designed and built, mainly for heavy ion nuclear physics [16]– [18]. This technology has generated a line of superconducting cyclotrons that soon may play a critical role for cancer treatment.

II. GOALS OF ACCELERATORS

A. Particle Physics and Accelerators

Accelerators are very powerful microscopes that can probe matter in very small detail. Indeed accelerators use particles at such energy that the associated wavelength $\lambda = h/p$, is very short, allowing details of the same order of magnitude to be resolved. In the LHC, where elementary collisions will happen at the TeV scale, the corresponding λ is 10^{-18} m: so we could rename our machines "attoscopes" [19].

By reaching the energy that is necessary to probe matter in such detail, we also recreate conditions that existed only at the beginning of our world. At the TeV scale to be reached in the LHC, we will recreate conditions that existed 1 ps after the big bang: accelerators are real time machines, too.

In the last thirty years, HEP has been able to give a fairly good description of fundamental constituents, all condensed in the so-called Standard Model (SM). However, the Higgs particle, absolutely needed for the consistency of the model, still escapes experimental detection. Moreover, although SM is a very detailed description, a few fundamental questions need still to be answered: i) why so many particles; ii) why so many forces; iii) what is mass, and why do particles have the masses they do? LHC should give a decisive contribution to the understanding and solution of these enigmas and should also provide information about other important questions, like the nature of dark matter and dark energy, and the scale of grand unification.

B. Why Do We Need Technology "at the edge" Like Superconductivity?

1) The energy frontier: synchrotrons, circular colliders

There are two routes to open new knowledge in particle physics, as illustrated by Fig. 1. One route is to access the highest energies, the so-called "energy frontier". In fact, by giving more and more energy to particles we can create new particles with rest mass equal to the kinetic energy of the accelerated particles, thus transforming energy into mass that is equivalent to looking deeper and deeper into sub-nuclear details, as mentioned above.

For the high-energy frontier, like the LHC, the accelerated particles are hadrons (mostly protons, sometimes ions) since for them the power lost by synchrotron radiation is small and therefore it is convenient to re-circulate the beam through short sections of radio-frequency cavities providing the accelerating electric field. Usually, two counter-rotating beams are collided continuously at a few points of the ring. Hadron colliders are thus circular and based on bending magnets.
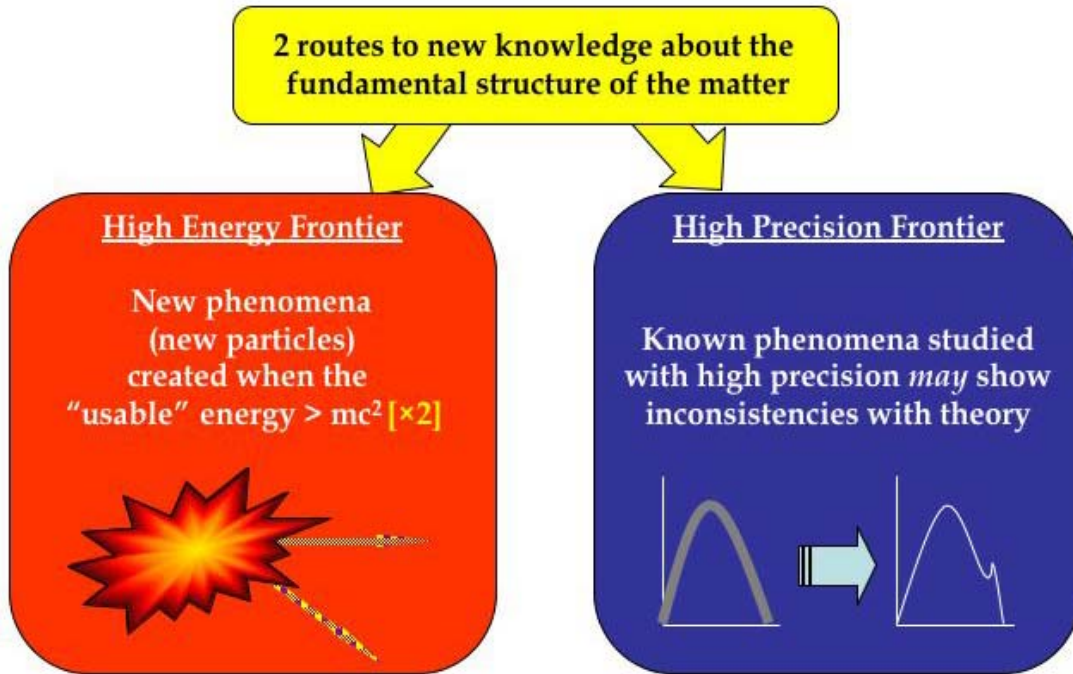
Fig. 1. High-energy physics two routes to discovery.

The energy of particle delivered by circular accelerators in relativistic regime can be written as [5]: $E \approx 0.3\,B\,R$, where the E is expressed in TeV, field intensity B in tesla and ring radius R in km. One can see that high field pays off as much as long tunnel length, hence the interest and the push towards high field magnets is understandable. Since the end of the seventies, all large hadron colliders built or conceived are based on superconductivity.

There are also stringent economical reasons that make accelerators a so-called "killer application", $i.e.$, where superconductivity is indispensable. The power dissipated in the resistive coils of normal conducting magnets scales as B R, $i.e.$, as the beam energy, while the cryogenic power needed for the superconducting magnet scales to first order as R only, which makes evident the advantage of choosing high field and "moderate" R in selecting the parameters of the collider. In reality, the previous scaling is only approximate since cryogenic power is affected significantly also by the operating temperature (1.9 K in the LHC rather than the 4.4 K used in other machines) and, for machines beyond the LHC energy, also by the synchrotron radiation power. LHC absorbs about 40 MW of electric power for the cryogenic plant cooling the super-conducting magnets of 8.3 T installed in the 27 km tunnel. Were normal conducting magnets operating at 1.8 T used, a 100 km long tunnel would have been required with an electrical power consumption of 900 MW, leading to prohibitive capital and operation cost [20].

2) High precision frontier: linacs

The second route is the "high precision frontier", where by means of leptons (usually e+e–) one can unveil information that can prove or disprove a theory. Although the energy is usually less than in hadron colliders, thanks to the cleanness of the particle-antiparticle annihilation,

previously known dependencies can reveal new details that can confirm or invalidate the Standard Model, see Fig. 1. This route is pursued by large electron linacs, like the proposed ILC (International Linear Collider) [21] requiring a massive use of rf cavities working in the range 0.1 to 3 GHz. In this case, the beam energy is expressed as: $E = e\,\varepsilon\,L$, where L is the length of accelerating cavities providing electric field ε, usually called voltage gradient by the linac community, and e is the electron charge. In the case of linacs, the comparison between superconducting and normal cavities is subtler. The highest gradients are actually reached with very high frequency copper cavities. However, the higher power dissipation, the smaller beam tube and the shorter bunches resulting from use of high frequency copper cavities makes superconductivity a much better choice, at least in the range of energy today attainable, 0.5 to 1 TeV in the center-of-mass. For these reasons, ILC, the next precision frontier machine, is being designed based on SC technologies. The same technology will be used to build a 2 km long SC linac that will proved 2.5 GeV electrons for the European X-ray FEL (Free Electron Laser) source just approved at Desy, Hamburg [22].

The better beam properties and the possibility to run in continuous mode (CW machines) also make superconducting cavities the preferred choice for the future 4th generation synchrotron light sources. We will not discuss further cavities and radio-frequency SC, leaving this topic to a more specialized paper.

C. Nuclear Physics and Medical Applications: Cyclotrons

In case of superconducting cyclotron, the proton beam is in the range of 50 to 250 MeV (20 to 200 MeV/u for ion beams, where u is the atomic mass unit), so the relativistic approximation used above in subsection *"The energy frontier"* is not valid anymore. However, the line of reasoning is still correct. A normal conductive system would employ water-cooled copper coils working at around 10-15 A/mm^2 and for a cyclotron this would require electrical power in the 1 to 10 MW range, depending on size and central field level, while the corresponding superconductive system would require about 10 to 20 times less power. In addition, there are considerations of magnetic field shape and of total mass: because the coils are much slimmer in the superconducting option, the required iron yoke –which is the dominant part of the total volume and mass – is considerably lighter than in the normal conducting case. Furthermore, the field shape related to small radial thickness makes beam extraction much easier in the case of SC option. In conclusion, although less stringent than in the HEP case, the advantage of SC is clear for systems that have to be hosted in hospitals, usually very sensitive to size limits, to power savings and to the operating cost. Superconducting cyclotrons are designed and manufactured for nuclear researches since more than 20 years, and here the choice is more obvious since the energy range demands a field level of 4 to 5 T, while a system for hadrotherapy requires rather 2 to 4 T. Despite these arguments, the first systems for hadro-therapy were built with normal conducting coils. However, the above mentioned reasons for superconductivity are increasingly accepted, thanks also to the reduced maintenance required by the cryogenic systems containing a set of low-cost cryocoolers, which condense the small quantity of helium vapor generated in the low-loss cryostat, a technique successfully employed in MRI magnets.

D. Particle detectors

Returning to accelerators for physical research, once the particles are accelerated and smashed one against the other, the new particles and radiation coming off the collision point need to be detected. To this aim, the collision points are hermetically covered by 4π detectors, intercepting

all collision products, except for a very tiny cone along the primary beam axis, see Fig. 2. Detectors need magnetic fields for charge determination and for momentum spectrometry, whose resolution scales as: $\Delta p / p \propto BL^2$, L being the path length in magnetic field, when tracking is inside the magnetic field. Hence, large volume pays off more than high field. However, in many cases, the parameters are such that SC magnets are necessary to obtain the necessary resolution.
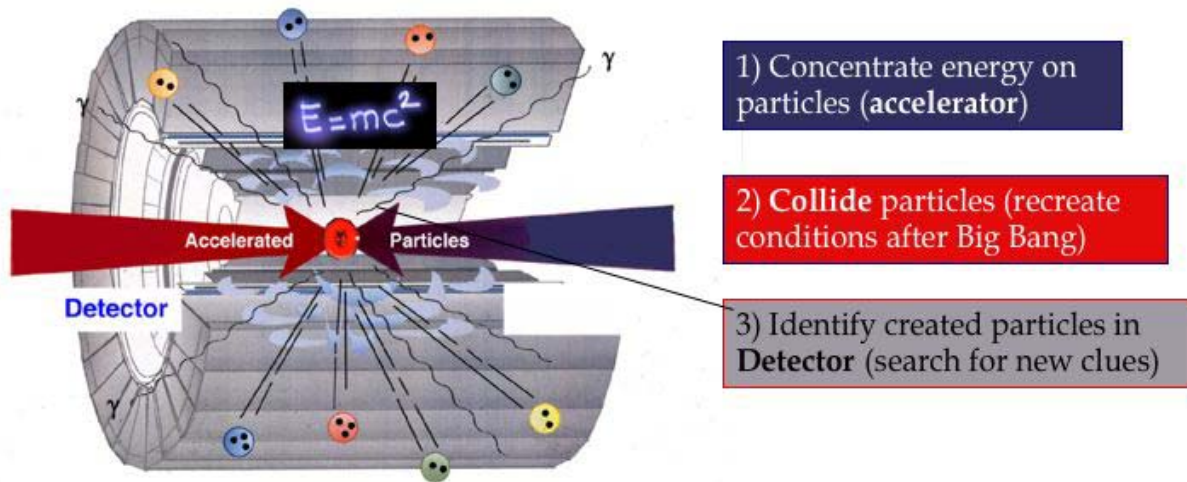
Fig. 2. Function of a particle and radiation detector.

In some cases the magnet is inside the calorimetric part of the detector: in these cases the magnet must be as transparent as possible to particle and radiation. Even if the field level is usually less than 2 tesla, these conditions can be achieved only by use of superconducting coils, because the corresponding thickness of a copper coil would be much larger, making again SC a killer technology for this application.

III. THE LARGE HADRON COLLIDER

LHC, the largest accelerator so far designed and built, is designed to provide collision at 14 TeV in the center of mass, with a beam current of 0.5 A. To do so, protons at low energy are injected from the existing SPS accelerator at CERN into the LHC main ring. Meanwhile the field of the dipoles is raised in 20 minutes from 0.45 T up to 8.3 T and the energy of the two counter-circulating beams is increased from 0.4 to 7 TeV. The main dipoles, and all other main systems, are designed for possible ultimate operation at 9 T. In order to attain such high field with well-proven Nb-Ti conductor technology, the magnets are cooled to 1.9 K by means of pressurized superfluid helium. In total, some 40,000 tonnes of mass are cooled to this low temperature, well below the ≈ 3 K residual temperature of the universe.

The LHC accelerator is complemented by four main experiments: ATLAS, CMS, Alice and LHC-b. The first two experiments are general-purpose experiments and the largest in size. Both use large superconducting magnets with 1000 tonnes cold mass for each.

The 3.8 m diameter tunnel located some 100 m underground, had been already built for the LEP project (an e^+e^- collider, which ceased to operate in 2000), while the ATLAS and CMS

experiences are located in huge galleries, see Fig. 3.

Fig. 3. The large ATLAS cavern in March 2004, ready to receive the ATLAS toroid. In the center, the tunnel of the LHC machine is also visible.

The LHC project (the machine plus experimental areas) should cost about 2.5 billion Euros (only material is accounted for). It is worth noting that the cryo-magnetic system takes the most of it, with 2/3 of the total budget allocated for.

The project was approved in its final configuration in December 1996, and it is expected to deliver beam collision starting late spring 2008. This is two years and half later than in the original schedule devised at the end of 1996, despite the budget difficulties encountered by CERN (magnet system overrun of 11%, civil engineering of 25%, *etc.*), the late start of the magnet industrial production, a few severe technical and organizational problems in the cryogenic distribution line, which runs all along the 27 km tunnel, and in the cryogenic/electrical distribution feed boxes.

IV. LHC MACHINE SUPERCONDUCTING MAGNETS

A. General and Historical Background

In order to obtain the desired field level and to meet efficiency and cost targets, the required overall current density for accelerator magnet is huge, around 400 A/mm^2 [23]. For comparison the average J in high field solenoids is around 100 A/mm^2 while for large fusion and detector magnets it is around 30-50 A/mm^2. Electromagnetic forces, F, are considerable and since the coil geometry is not self-supporting, (see Fig. 4) the containment of the conductor is critical both for stability (see later) and for field quality. The beam circulates 500 million times before being exhausted. The field accuracy must be controlled for each single harmonic at the level of 10-100 ppm, in a region very near (1 cm) the coils.
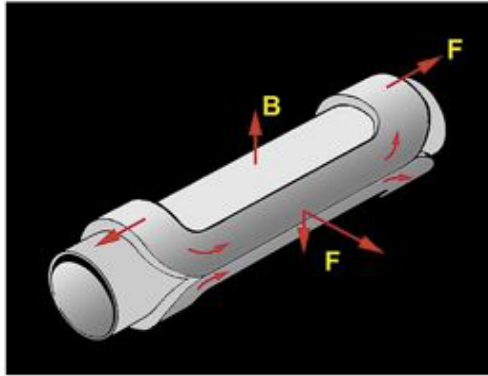
Fig. 4. Basic shape of a dipole coil. Forces on the winding, *F*, are indicated by arrows.

Another main characteristic of the LHC is that each electrical circuit consists of many magnets supplied with current in series: there are 2×154 dipoles for each of the eight dipole circuits, and there are 45 quadrupoles for each of the sixteen main quadrupole circuits. This implies that:

1. The magnets must be equal in bending strength, B L, to within 0.1%. This was not an easily attainable goal, considering that LHC magnets were built in different production lines in different countries.
2. The magnet worst in quench performance will determine the final energy of the accelerator, without the possibility of compensating weak magnets with stronger ones.

Accelerator magnet operates near the critical surface: LHC dipoles operate at 8.3 T, *i.e.*, 85% of I_c measured on the load line, and can even operate at 93% (ultimate level of operation). This fact, together with the low content of stabilizer (typically 60% of the conductor cross section) implies that these magnets do train. This is the price to be paid for this very high field level when using Nb-Ti. In Fig. 5 shown are the cross sections of the principal hadron colliders main dipoles. One can see that the cross sections look similar, but with two remarkable exceptions: i) the Tevatron, the pioneer, employed room temperature iron yoke, while all subsequent projects followed the line of HERA (derived from Isabelle, see Table I) in having cold iron (less He consumption, more time to cool down and warm up); ii) the LHC has chosen a very compact design where the two beam channels are located in the same cold mass, following the Two-in-One concept.

B. The LHC Magnets
1) Superconductors
Almost all magnets in the LHC main ring are superconducting, wound from Nb-Ti based conductor. In order to get the maximum field level [19], the decision was made to operate at 1.9 K in a pressurized (1 bar absolute) superfluid helium bath. At 1.9 K the Nb-Ti critical current is enhanced by 3 T with respect to the 4.2 K critical current. The actual gain in field obtained in a magnet is about 2 T, thus permitting operation at 8.3 T and possibly at the ultimate field of 9 T.
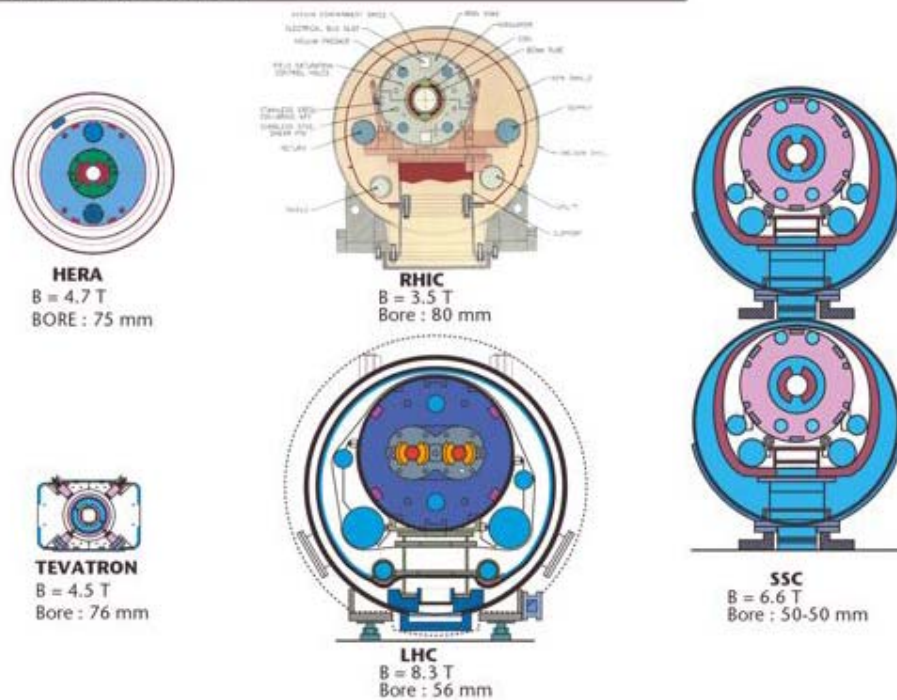
Fig. 5. The historical comparison of dipole sections in main HEP projects based on SC magnets.

For the LHC machine, the total quantity of superconducting cable is 7600 km, or 1200 tonnes, necessitating more than 400 tonnes of Nb-Ti ingots of very high quality and homogeneity (at 0.1% level). To guarantee the necessary quality control, many specific procedures have been implemented, from SPC (Statistical Production Control), to new tools checking automatically for cabling errors like strand crossovers, Sn-Pb inclusions, sharp edges. An updated report on superconducting cables for the LHC is given in [20]

The critical current density of the whole cable production for the outer layer of the dipoles and for the quadrupole has exceeded the specification with a 5-10% margin, little cabling degradation (2-3%) and an excellent uniformity [21]. Given the fact that magnets operate so near the critical point, precise knowledge of the transport properties is critical: therefore, each billet has been qualified with at least one measurement of I_c vs. field in the factory (at 4.2 K) and one at CERN at 1.9 K (typically 2-3 measurements per billets were made); in addition about 25% of the finished cable units have been measured and a few percent at 1.9 K. The critical current of the whole production of one type of cable is shown in Fig. 6.

Superconductor magnetization is very important for accelerator magnets since it is the main source of field imperfections at injection energy. Much effort was expended to control the magnetization, however a number of billets above specification had to be accepted. In a few cases the values were so high as to cause rejection of the billet. Large magnetization values have been traced to insufficiently controlled conditions during extrusion. However, through proper dilution of the high magnetization strands in cables dominated by low magnetization strands, it was possible to accept almost all of the production. This implied a remarkable effort of measurements at 1.9 K in the CERN superconducting laboratory.
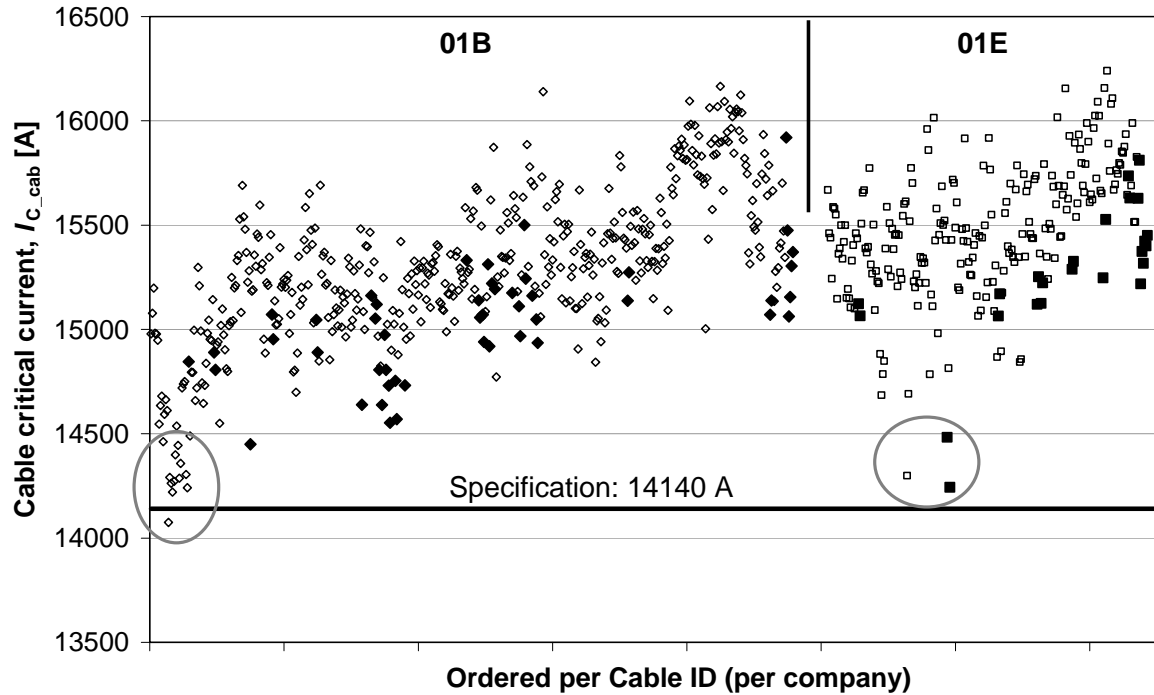
Fig. 6. Critical current measured on cable type 01 (from two companies here indicated as B and E) for the whole production. Empty symbols refers to measurements done in BNL-USA, solid symbols in CERN.

The uniformity of interstrand resistance in the cable is important for controlling the field quality during the ramp up of the beam to flat top energy. The novel solution adopted for the LHC is based on coating the strands with a SnAg alloy, before cabling. After cabling, the cable roll is then exposed to a controlled heat treatment in air in order to oxidize the cables. This method is simple, cheap and suitable for Rutherford cabling techniques, but required many adjustments and practical R&D to become reliable in industry. It has been certainly one of the keys to the success of the LHC cables (see Fig. 7).
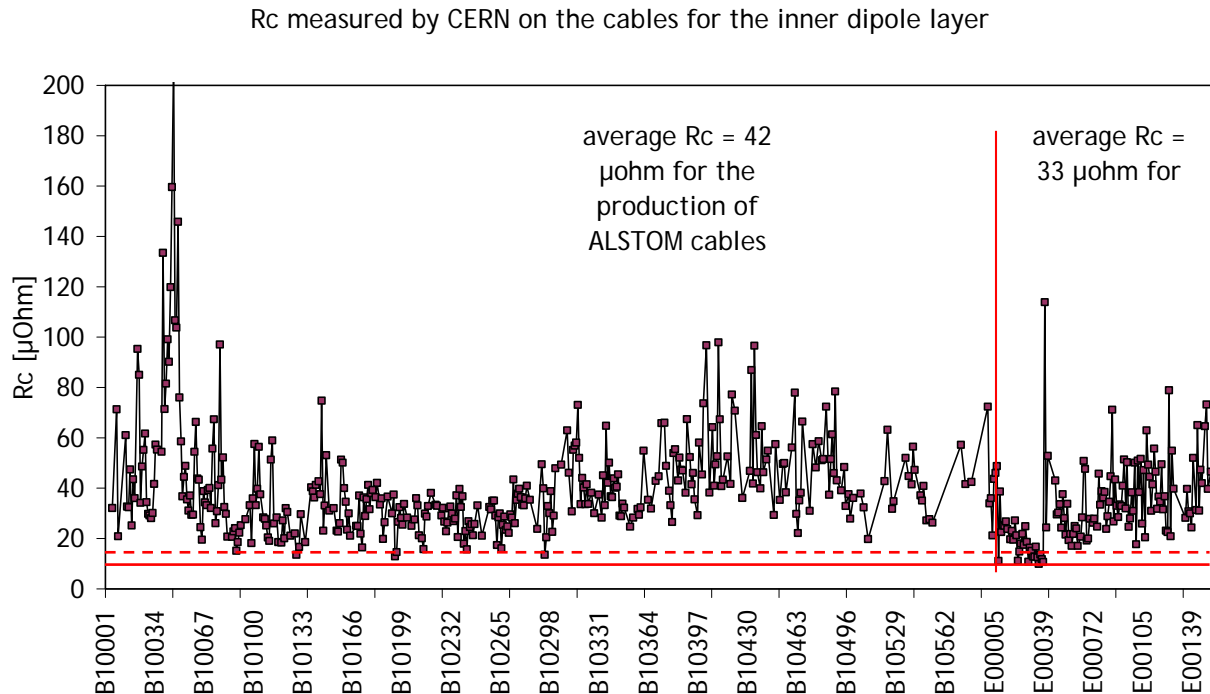
Rc measured by CERN on the cables for the inner dipole layer

Fig. 7. Inter-strands contact resistance for the LHC cable 01, compared with target (dashed) and hard limit (solid horizontal line).

2) Dipole magnets (MB, magnet bend)

The design of LHC magnets went through about ten years of evolution with three generations of design. The three generations differ in the coil layout, in the collar design and on how the coil-collar assembly interferes with the yoke-skin assembly. The basic design characteristics [22] of the present third and final generation are:

a) Collared coil

It is based on six conductor blocks, optimized to place conductors as radial as possible to minimize shear forces. The design was further optimized twice during series construction, to obtain the desired field shape at better than 10 ppm [23]. The coils feature two layers, wound with two cables having margins in critical current very similar.

Due to the lack of stabilizer, to the very high current density and to the small operational margin, the quench energy is very small, ranging from tens of µJ to mJ. In such conditions, tiny movements of a few µm can trigger an irreversible transition. From this comes the great importance of the mechanical structure, and namely the collars that surround the coils (see Fig.8).

Collars have been designed as twin-type, a particular variant of the two-in-one where the two dipoles are coupled mechanically and also magnetically (no iron separation between the two coils). They are made of special austenitic steel with very low magnetization $\chi_m < 0.005$ under operating conditions [24]. Collars not only sustain forces and limit conductor movements. They also give the right shape to the coils, an important issue in magnets where field accuracy is required at 1 cm from the conductor.
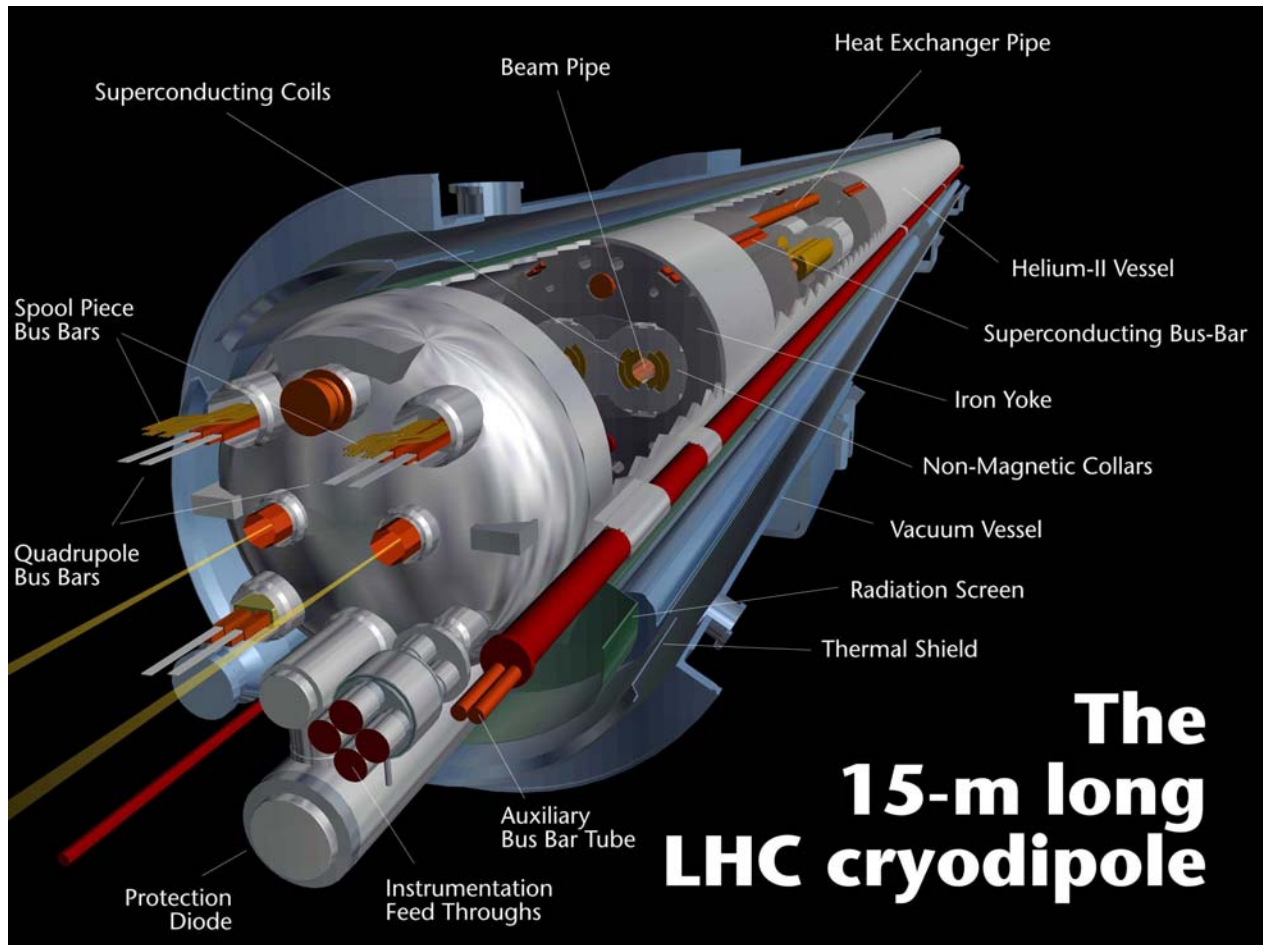
Fig. 8. Artistic view of the LHC main dipole.

b) Iron yoke and cold mass assembly

Iron yoke: it not only serves for flux return, but it also adds about 15% to the field. An iron-free design would have only few percent less of central field, at the price of a much higher operating current, resulting in more difficult operation and protection, in addition to the severe problem of high stray field.

The magnet is curved, with a radius of curvature of 2812.36 m, which make, over the 15 m length, a sagitta of about 9 mm. This curvature has a tolerance of ± 1 mm, with the exception of the extremities of the magnet where the tolerance is very tight: ±0.3 mm (systematic) and 0.5 mm rms in order to keep the corrector magnets centered with respect to the beam tube - to avoid harmonic feed down (detrimental for beam optics).

3) Quadrupole magnets (MQ)

Quadrupole magnets are necessary for focusing the beam and in the LHC they are of numerous types. Those classified as arc quadrupoles, or main quadrupoles MQ [22,26], number 360. They are located in the Short Straight Section (SSS) cold mass, which comprises also different types of corrector magnets[1]. Other quadrupoles are assembled in Special Short Straight Section cold masses (S4) and their total number is 142, a few working at 4.4 K and others at 1.9 K, like the

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[1] Definition of cold mass is given on p. 12.

main quadrupoles and main dipoles [27]. All quadrupoles are of the two-in-one type, *i.e.* the coils for the two-beam channel are in the same iron yoke, while each coil is collared as single unit. The collared coil is a freestanding unit in the iron yoke, *i.e.*, collars support all the forces, see Fig. 9. These quadrupoles are much shorter than the dipoles, ranging from 3 to 4.5 m. However, the cold masses range from 7.5 m of the arc SSS to 15 m for some S4 where two main quadrupole magnets or many large correctors are assembled in one S4.

A further family of important quadrupoles consists of the interaction region (IR) quadrupoles. These are the 32 quadrupoles to provide the strong focusing of the beams at the interaction points. These magnets are the ultimate determinant of the luminosity, a parameter defined as the collision rate times the cross section and that, after the energy, is the most significant measure for the collider performance.
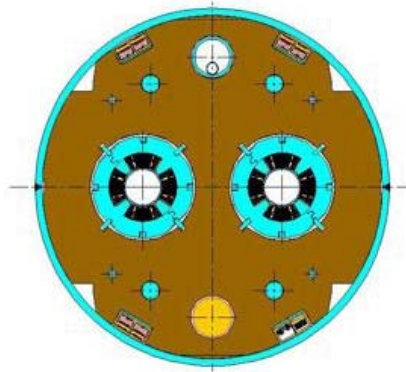

Fig. 9. LHC quadrupole for the matching sections. The two bores are surrounded by the four coils. The coils of each bore are encased in a collar structure and the two collared coils are in a unique iron yoke.

These quadrupoles are single aperture magnets with a coil bore of 70 mm (versus 56 mm for the main dipoles and quadrupoles). Because of the high gradient and large aperture, the peak field in these quadrupoles is near the peak field in the dipole. Operation at 1.9 K is required both by the peak field value and by heat removal: indeed, because these magnets get a considerable part of the collision debris escaping from detectors along the beam tube, they have to be stable against continuous energy release of 3 mW/cm^3; this means 30 W per magnet. These special IR quadrupoles, together with the 16 associated superconducting dipoles for beam merging and separation, are a special contribution of the US DOE laboratories (Fermilab, BNL and LBNL) [28] and of Japan (KEK) [29].

4) Magnet performance

The magnets are delivered as cold masses to CERN. A cold mass is the assembly that comprises coils, mechanical structure, iron yoke and helim vessel. At CERN the following tasks take place: i) cryostat assembly; ii) cold test (power and magnetic field measurements); iii) preparation for the tunnel with insertion of a beam screen to intercept the synchrotron radiation (that otherwise would constitute an unacceptable load on the 1.9 K cryogenics); iv) transport in the tunnel; v) interconnections between magnets. Eventually cool down and energization in the tunnel can start, an operation that is being performed at present.

Magnetic measurements at room temperature have been done in industry on all magnets [30], to early intercept assembly faults. Cold test at CERN of all individual magnets has allowed intercepting a few magnets with weak quench performance or showing electrical faults. In Fig. 10 the quench performance at first thermal cycle of the dipoles tested so far is shown [31]. Magnets

reaching nominal operation in two or less training quenches (nearly 90% so far) are considered good. Some of the others are submitted to a new thermal cycle and then re-tested. Usually their performance improve, i.e. they keep memory of the previous training quench. In total only 2.5% were found defective: half for electrical problems (mainly quench heater damage) and half for quench performance. Almost all have been repaired and returned to CERN.

In addition to the measurements in the factory, carried out at room temperature by powering the magnets with a few amperes, about 10% of the dipoles have been fully measured to assess the field quality content.
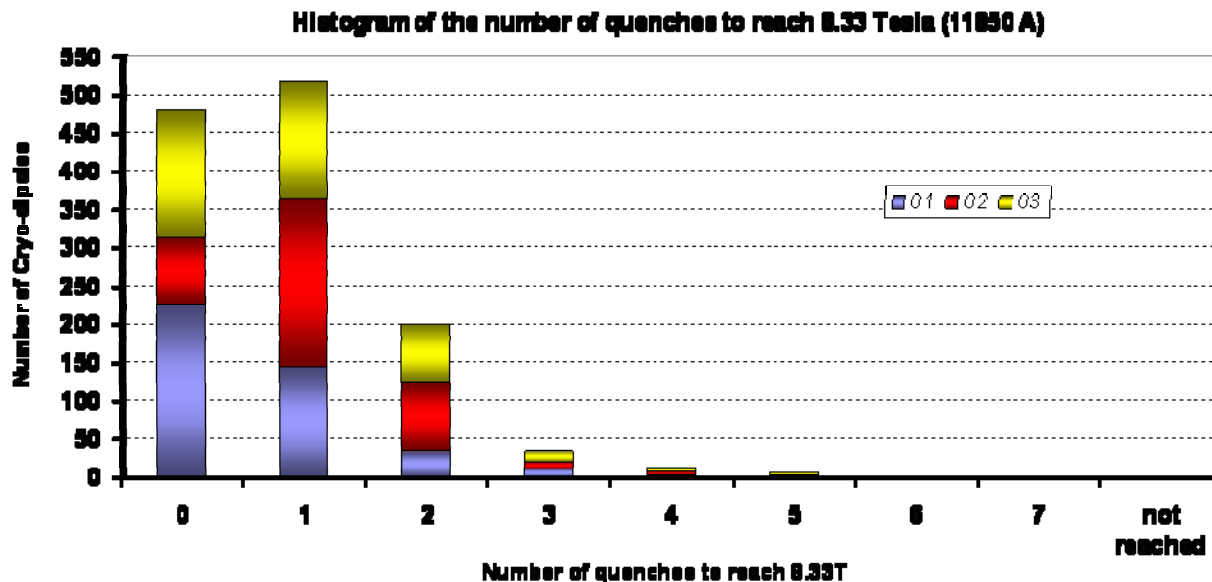

Fig. 10. LHC dipole quench performance at first thermal cycle. Different colors refer to the three different manufacturers.

Measurements in superconducting state permitted the evaluation of field errors coming from persistent currents and snap back, an effect where the magnetization slowly decays and then "snap back" suddenly to its previous value. Both effects are of great importance for the initial phase of the acceleration process [32].

V. DETECTORS

A. Introductory Remarks

We mentioned that detector magnets are usually of large size and moderate field. In the LHC the size is extremely large, 25 m long for the ATLAS Barrel Toroid (BT), and the field is not so low, 4 T in the center of the 12 m CMS solenoid. So the challenge is quite serious. A further characteristic typical of detector magnets 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 scarce: basically physicists would like a magnetless field. Magnet size and the high stored energy (CMS is the champion of SC magnets with its 2.7 GJ of stored energy), implies that superconducting design of detector magnets is dictated by two factors: 1) magnet protection, since in any case and whatever scenario the risk of loosing the magnet cannot be tolerated in view of the cost and of the fact that the whole detector is built around the magnet; 2) magnet stability, since, given the dimensions, perturbations are large and if a magnet quenches, it will mean loss of a few weeks of

detector data taking. The issue of magnet stability is made even more crucial by then fact that all these magnets are impregnated and indirectly cooled.

B. Conductor Technology

Both ATLAS and CMS magnets are wound with Cu/Nb-Ti flat Rutherford cables embedded through co-extrusion in a pure aluminum matrix, a technology developed and well established for detector magnets. Bonding values between cables and aluminum above 15-20 MPa are required. To assure this value over the 100 km long production needed for the two experiments, an extremely careful Q.A. plan and tooling were set up. A new device, based on an ultrasound scanner that is able to continuously monitor the bonding by means of imaging analysis has been developed. Co-extrusion parameters have been carefully studied during the R&D phase, to avoid a severe reduction of the critical current: the goal is usually to limit critical current, I_c, degradation to less than 10% from virgin wire. Given 2-4% of degradation for cabling, this allows only 6-8% degradation for co-extrusion. 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.11 that this goal is at the limit of present technology.
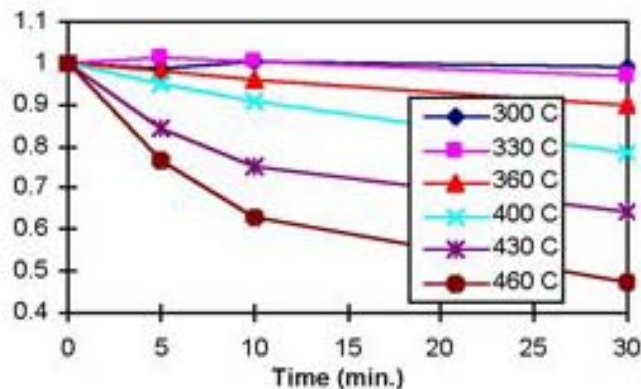

Fig. 11. Critical current degradation of Cu/Nb-Ti versus thermal treatment simulating co-extrusion conditions.

A very good resistivity ratio, RRR, of the aluminum can be achieved by using commercial, but expensive, aluminum 99.998%, (RRR greater than 2500 in the billet) and by carefully controlling the cleaning of the press. Values of 1200 and more have been achieved in ATLAS and CMS finished conductor.

A further parameter that has to be optimized is the contact resistance between cable and aluminum matrix. Indeed the bonding is given by the copper-aluminum inter-metallic layer, typically 1-2 μm thick. Lack of the inter-metallic layer generates a region of bad bonding, and even bad electrical contact between cable and stabilizer. But a too thick inter-metallic barrier, whose resistivity is pretty high, can increase the contact resistance above optimal values, thus reducing the stability (see later in the paper). For ATLAS and CMS an inter-metallic thickness of less than 3 μm assures contact resistance of less than 10-11 nΩ· m at zero field, which has been proved to be largely sufficient for stability according to measurements made in a large (9m x 5 m) model coil called B0 [33].

Generally 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 at 5 T, 4.2 K and the cost of the ATLAS magnet system (one of the largest and most

complex superconducting magnet systems) is less than 90 M€.

Indirect cooling and large current, 20 kA, call for low resistance of joints between conductors, less than 0.5 nΩ in magnetic field. 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 effect usually requires short junction length, while good contact resistance calls for a junction as long as possible (since a resistive barrier, the aluminum, is present). For ATLAS, an accurate modeling study confirmed by experimental results has fixed the optimal length to be around 2.5 m.

C. Stability and Protection
1) Stability and margin

Cooling capacity is large and supercritical helium flowing in the channel can remove from hundreds of watts to tens of kW. But there is considerable thermal resistance between the coils, where heat is generated, and the cooling channels where heat is eventually removed. So there has to be a fairly good enthalpy margin. For ATLAS BT, for example, the choice has been $\Delta H \approx 2$ kJ/m^3, that is accomplished by a temperature margin $\Delta T \cong 6.8 - 4.8 = 2$ K (where 6.8 K in the transition and 4.8 K the operating temperature) . This margin, together with the good conductivity of the matrix, can also cope with an internal joint of moderately high resistance.

Given the amount of stabilizing aluminum in the conductor cross section, 400 to 600 mm^2, the MPZ (Minimum Propagating Zone) length is about 1 m for ATLAS toroids and the CMS solenoid. The MQE (Minimum Quench Energy) against point disturbances is about 5 J.

Both the enthalpy margin and the 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. Given the margin and the fact that the conductor cross-section is dominated by the matrix, J_c is never an issue, because it can be compensated largely by an increase in Nb-Ti cross section, without prejudice to the stabilizer content.

2) Protection

The amount of stabilizing aluminum is eventually determined by protection consideration. Indeed, we need to buy time to safely detect (and with certainty, to avoid useless fast discharge) the quench onset in such a large coil. Furthermore, time is needed to extract energy and/or to spread energy into the coils to avoid dangerous hot spots, too high thermal stresses and unsustainable voltages. The main reasons for large conductors can therefore be summarized as: large current, in order to have low inductance, and large stabilizing cross section to lessen the J_{stab} after transition.

All magnet systems of ATLAS rely on heaters. In all cases, it is necessary to spread out the quench rapidly. In the case of the toroids, since the quench margin is so huge, about 5 kW of heater power has been installed and accurate studies to select heater positions have been carried out. A very effective technique to spread out a 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. In case of CMS, a more classical system based mainly on an external dumping resistor has successfully been installed. In this case, the cold mass rise in temperature is less than in the case of spreading the quench inside: the price to pay is however a larger voltage across the coil terminals, about 1 kV.

Protection and stabilization both demand a matrix having very high conductivity. This is "easily" accomplished by using pure aluminum, as previously mentioned. It is worth noting that RRR = 1000 at zero field becomes 400 at 1 T. For higher fields the Al magnetoresistivity

saturates, which is another advantage of pure aluminum over copper.

To conclude this overview of protection, it is instructive to consider the graph shown in Fig. 12, where most of the main solenoidal detector magnets built so far are represented in a plot of energy/mass *versus* energy. The plot should be complemented by other information: for example thin solenoids like ZEUS and ATLAS have more and tighter constraints than the muon chamber magnets like Delphi, Aleph and CMS. However, the graph shows the great 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].
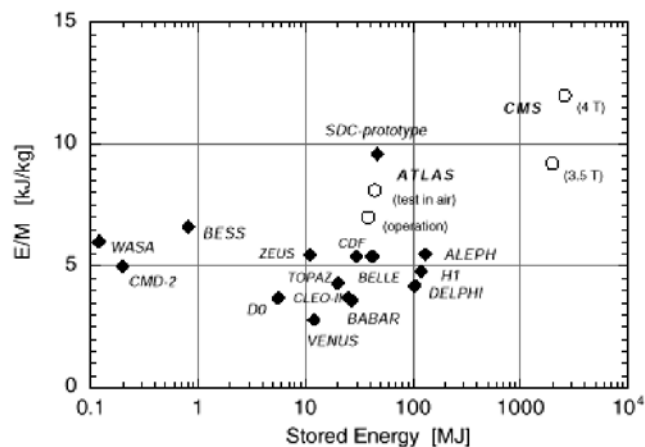
Fig. 12. Stored energy per unit cold mass versus stored energy for many HEP detector magnets. Open symbols refer to LHC detector magnets.

D. ATLAS: the Giant Toroid

Effectively, because of a certain interest in having the whole detector to be practically iron-free - to avoid multiple scattering limitations in the devices that detect the particles, the toroidal configuration is more and more considered for detectors. The ATLAS collaboration, 1800 physicists and engineers from 164 universities and institutes from thirty-five countries, has designed and built a complex system composed of four large magnets.

The first is a large (25 m long, 5 m wide) toroid covering the whole length of the detector, called the barrel toroid (BT), see Fig. 13. This toroid is composed of 8 coils and it serves as the main mechanical structure of the detector. Two end cap toroids (ECT) close the barrel toroid and take care of bending the forward particles. ECT and BT are powered in series and share the same protection and cryogenic system.

The inner solenoid is 2.4 m in diameter and 5.3 m in length. By generating a field of 2 T it provides an optimized bending for particles inside the trackers. In order to minimize the room allocated to the mechanical structure, a special aluminum alloy has been developed. It shows a modest decrease in RRR while the yield strength of it is increased to 130 MPa. This allows the aluminum, whose presence is necessary for protection and stability, to be used also for force containment.

Both the solenoid and the barrel toroid have been already successfully tested in their final postion in the cavern [36], [37], while the two ECTs are being installed and their test in the cavern is foreseen later in 2007 [38].
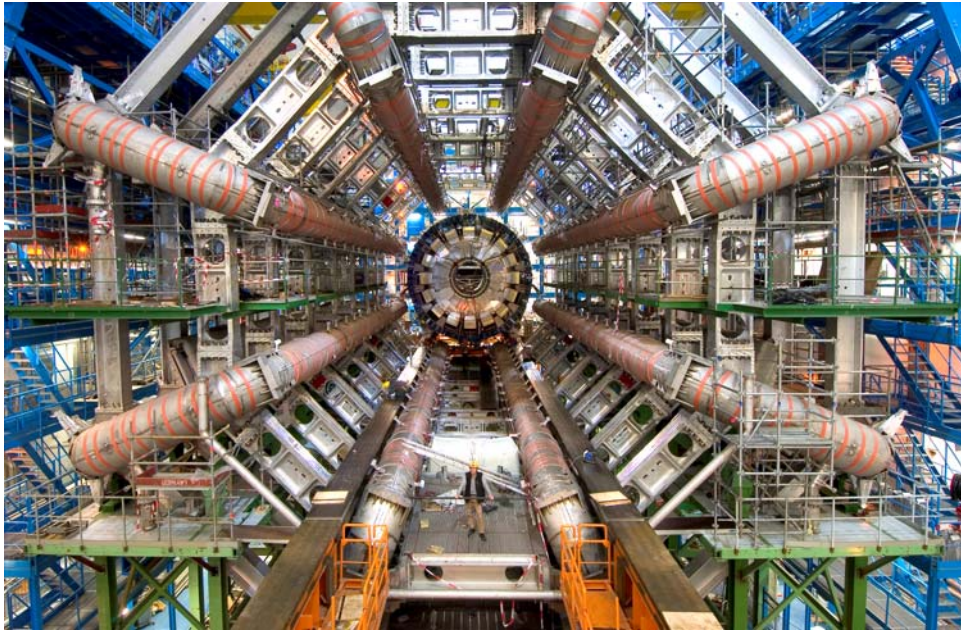
Fig. 13. The ATLAS BT magnet after installation in the cavern.

E. CMS: the Most Powerful Solenoid

CMS, designed and built by a collaboration of the similar size as ATLAS, employs a more classical configuration: a large solenoid whose coil is placed outside the calorimetric part. Given the size, 7 m in diameter and 13 m in length, and the 4 T field level, the stored energy is exceptional: 2.7 GJ. Powered up to nominal field first on August 29, 2006 [39], it holds, presumably for long time to come, the world record as steady magnetic energy storage. The hoop forces are so high that, despite a 50 mm thick restrain cylinder, made out of strong Al alloy, the conductor must have a special reinforcement, as previously mentioned. The winding has to assure good field uniformity despite the rigidity of the conductor: the coil has been wound from the inside onto the restraining cylinder by pre-bending the cable and positioning it by means of a robot.

In Fig. 14, the CMS magnet is shown before its first excitation, still on the surface. In summer 2006 the solenoid has been successfully excited to maximum current in a test on surface and is now being assembled in the underground cavern.

January 2006: End of the CMS Magnet Manufacturing

Fig. 14. CMS solenoid inside the dodecagonal iron yoke.

VI. FUTURE PROJECTS

A. Fast Cycling Magnets for FAIR (GSI)

The main accelerator projects based on superconducting magnets that are under study in Europe concerns mainly two lines: fast cycled magnets and high-field magnets.

A large accelerator complex for Anti-protons and Ions at GSI in Darmstadt, Germany, called FAIR, has been proposed in 2003 [46]. The multi-purpose nature of the project translates in a quite complex system of accelerators, beam lines and detectors, see Fig 15. The scope of the project, among many, is to test quark-gluon plasma at conditions different than in the LHC: lower temperature but higher density, more similar to the one existing (supposedly) in neutron stars.

Fig. 15. The accelerator complex for Antiproton and Ions at GSI. Left: the existing facilities; right: artistic view of the new facility (FAIR). In light blue is visible the footprint of the ring that hosts SIS100 and SIS300 accelerators.

In terms of magnet technology the most interesting parts are the two 1 km long rings, named SIS100 and SIS300. Both are synchrotrons with beam rigidity of, respectively, 100 and 300 T·m, which means that the last can accelerate heavy ions like uranium up to 34 GeV/u. Here the beam is not held in colliding mode, rather it is directed against a target. Because most of the phenomena that are to be studied are based on rare events, high beam intensity and high repetition rate are primary goals for these machines. The repetition rate is about 1 Hz, *i.e.*, the magnet must be charged from low current up to maximum current, stay at the flat top for short time and then return into initial condition in about 1 s. Ramping the field up with beam implies that the desired field quality must be maintained also through dynamic conditions.

For SIS100 dipoles of peak field of 2 T and 4 T/s a suitable ramp rate is required. A careful study by the GSI laboratory has shown that the resistive option, albeit possible, would have resulted in a larger capital cost, not to mention the much higher operational cost related to electricity prices [47]. This result may be surprising but it can be well explained by the Fig.16 where the cross sections of the magnet built with normal conducting coils (left) is compared to the same field level magnet based on superconducting coils. Due to the coil size the iron mass gets enormous in the normal conducting case, such that its cost outweighs the cost of the cryogenic plant.
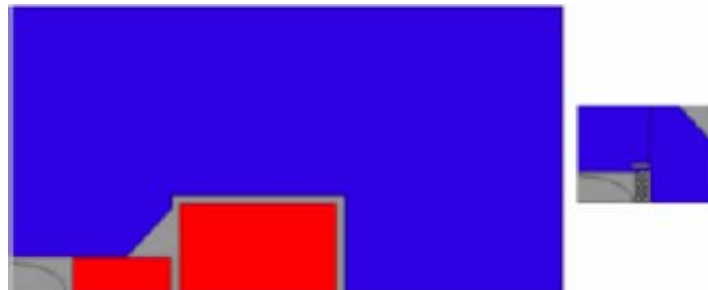

Fig. 16. Comparison between magnet options for FAIR SIS100. Only one quarter of the magnet cross sections are shown: left the normal conducting option (very large coils in red leading to enormous iron yoke, blue); right, the SC option where the tiny grey coils leads to a much smaller iron yoke (courtesy of G. Moritz, GSI).

The design of the SIS100 SC dipoles is similar to the Dubna Nuclotron magnets, based on window frame coils that have the main function of exciting a light iron yoke while dissipating as low energy as possible at 4 K. The conductor is basically an internally cooled copper hollow tube on which superconducting strands are soldered, see Fig. 17 [49].
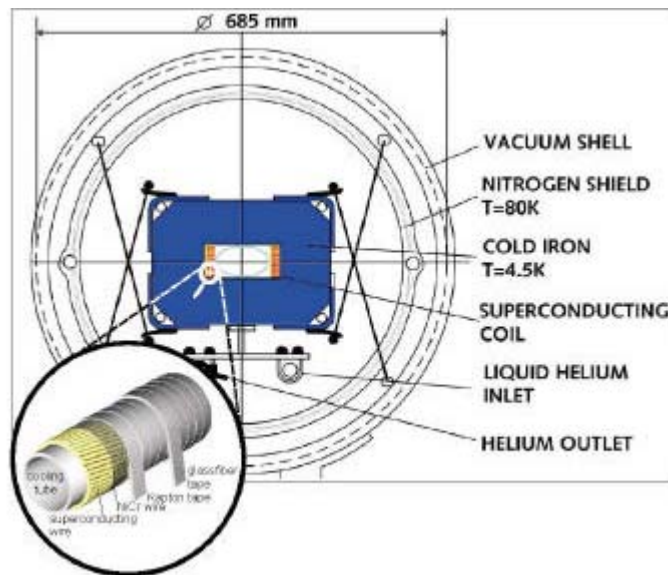
Fig. 17. SIS 100 dipole cross section, derived from Dubna Nuclotron design.

For SIS300, two designs are today pursued for the main dipoles [50]. The first, a collaboration between GSI and IHEP in Protvino, Russia, is based on a straight magnet with the maximum field of 6 T, wound with classical Cu/Nb-Ti Rutherford cable. The alternative design, pursued in the GSI-INFN, Italy, collaboration, features a longer, curved dipole, with the maximum field of 4.5 T, also based on classical cable, see Fig.18. In both cases, the main challenge is the low loss at low temperature, below 10 W/m. The compact coils in form of round shell are not the best in terms of heat removal. Other types of cable and coil shapes are by far less efficient in superconductor use and conductor positioning accuracy. The key goal is a very low loss cable, which implies filaments as fine as 3 μm or less, matrix in cupro-nickel or Cu-Mn, coated strands and also a stainless strip between the two faces of the cable to cut inter-strand losses. Very fine Nb-Ti filaments and low magnetization are necessary also to avoid severe field distortion at injection, due to persistent currents, while low coupling, intra- and inter-strands, avoids field errors during ramp up. Of course not only the superconductor and winding are critical: about 40% of the losses happen in the iron yoke which must be optimized, too.
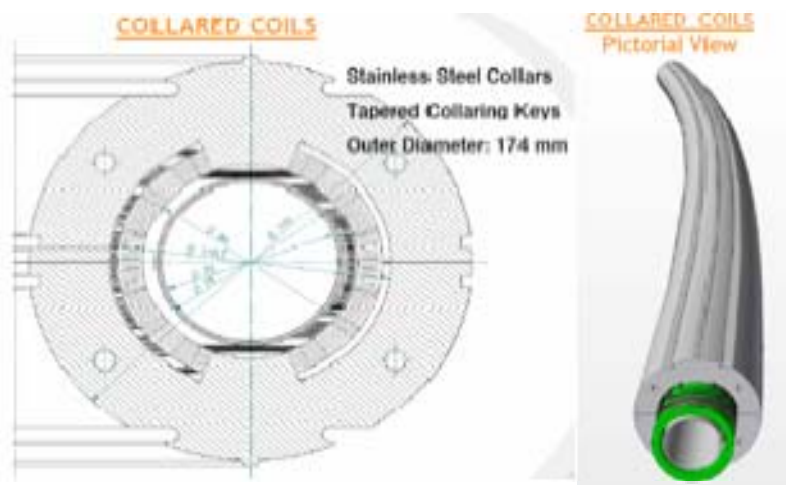

Fig. 18. Cross section and longitudinal view of the SIS300 4.5 T dipole coils. Courtesy of M. Sorbi, INFN-LASA, and ASG, Genova.

B. Cycling Magnets for the CERN Injector Upgrades

CERN is considering, as soon as the LHC is finished and paid for, to improve the old accelerator called PS, which is the workhorse of the physics program [51]. It takes the beam at 1 Gev from a small energy pre-injector and then delivers a 26 GeV proton beam into the SPS, the 450 GeV injector of LHC. Today the PS is a 600 m long synchrotron based on normal conducting magnets. An eventual upgrade, at present under preliminary design, could employ either superferric magnets, working at 1.8 T with an iron yoke and pole excited by a superconducting line or coil, or slim superconducting coils, which have potential for 3 T. The parameters are similar, but even more relaxed, than the ones of the FAIR SIS100 magnets previously mentioned; the decision will based on economical reasons. The magnet line will be 400-500 m long.

On a longer time scale, *i.e.,* after 2015, CERN is interested also to double the energy of the existing SPS, which is sited in a 6 km long underground tunnel. This would call for substituting the 4 km long line of iron-dominated magnet with superconducting magnets. Here, the parameters are very close to the FAIR SIS300 magnets, and in particular to the low field option [51].

C. High Field Magnets for LHC Upgrades

Despite the fact the LHC is not yet commissioned, future upgrades are planned at CERN. Indeed the full development of magnet beyond 10 T, making use of Nb_3Sn, requires many years of sustained effort and a considerable amount of resources. For the moment a plan for increasing the luminosity (see subsection IV.*B.3* for definition) foresees changing of the IR quadrupoles with very large aperture and long quadrupoles still based on in Nb-Ti. Then a further upgrade around 2016 would be based on quadrupoles (and dipoles) wound with Nb_3Sn. To this aim, a strong program on quadrupole development is going on in the USA (LARP program) [52]. In Europe a more modest, but hopefully increasing effort is driven by the NED program (EU supported CARE program) aimed at developing a cable of 3000 A/mm^2 at 12 T, 4, 2 K, with effective filament size of 50 μm in a large diameter wire. The cable should then be used for winding the coils of a 15 T, 88 mm free bore dipole, if adequate funding will be assigned.

D. Superconducting Cyclotrons for Hadron Therapy

As mentioned in section II.*C*, cancer treatment by use of protons and heavy ions, or hadron therapy, is becoming a medical tool. Recently the company ACCEL Instruments, GmbH, in Germany has achieved a breakthrough by designing and building a SC cyclotron [53] capable to accelerate a 250 MeV proton beam with a very compact machine having an outer diameter of only about 3 m, shown in Fig. 19.
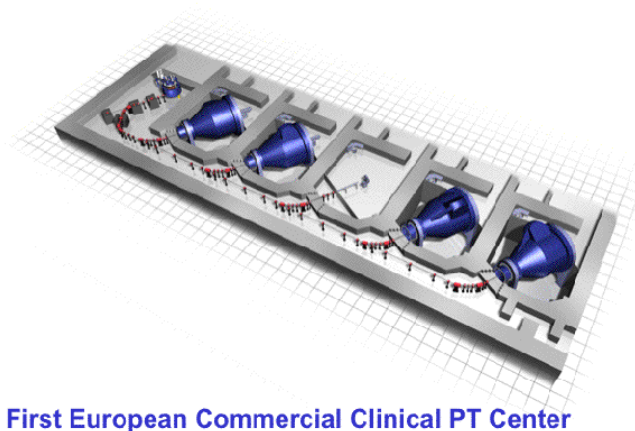
Fig. 19. Picture of the first SC cyclotron for proton therapy (ACCEL Instruments, GmbH, Germany). The upper pole is lifted. On the top right one can see the cryogenic box.

ACCEL has installed its first SC cyclotron in the PSI institute, near Zurich, Switzerland, which is in operation for patient treatment since February 2007. The company has also designed and built a whole proton therapy system for the RPTC treatment center in Munich, Germany. The heart of it is again a SC cyclotron but the facility comprises a complete system, many transfer lines and large gantry magnets. Studies to make these gantries more compact and lighter by using SC are going on in many places, so far without (to our knowledge) commercial success. In Fig. 20 it is possible to observe the impressive complex, now almost ready. Its commissioning now commenced and is expected to be finalized soon, after an intermission due to contractual issues.

ACCEL has been recently purchased by Varian Medical Systems, which suggests that large-scale success of this technology is expected. Superconducting cyclotrons for the acceleration of, *e.g.*, carbon ions for treatment purposes are also being considered as a suitable alternative to synchrotrons. Cyclotrons produce a continuous and relatively stable beam, which is advantageous for modern scanning beam delivery techniques.

Fig. 20. The impressive complex based on SC cyclotron, visible in the top left corner. The four large cones are four treatment rooms. Whole design and construction by Accel, GmbH.

VII. CONCLUSIONS

The LHC is one of the largest scientific enterprises and the largest application of superconducting and cryogenic technologies. Its construction relies on custom design and on manufacturing technologies that, although difficult, can be considered industrially matured. Its inauguration at full energy is expected in less than one year and, hopefully, this will be only a milestone of a long and durable development of SC for accelerators, as one might expects from the list of large future projects in Europe.

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