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**

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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, superstabilized 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.

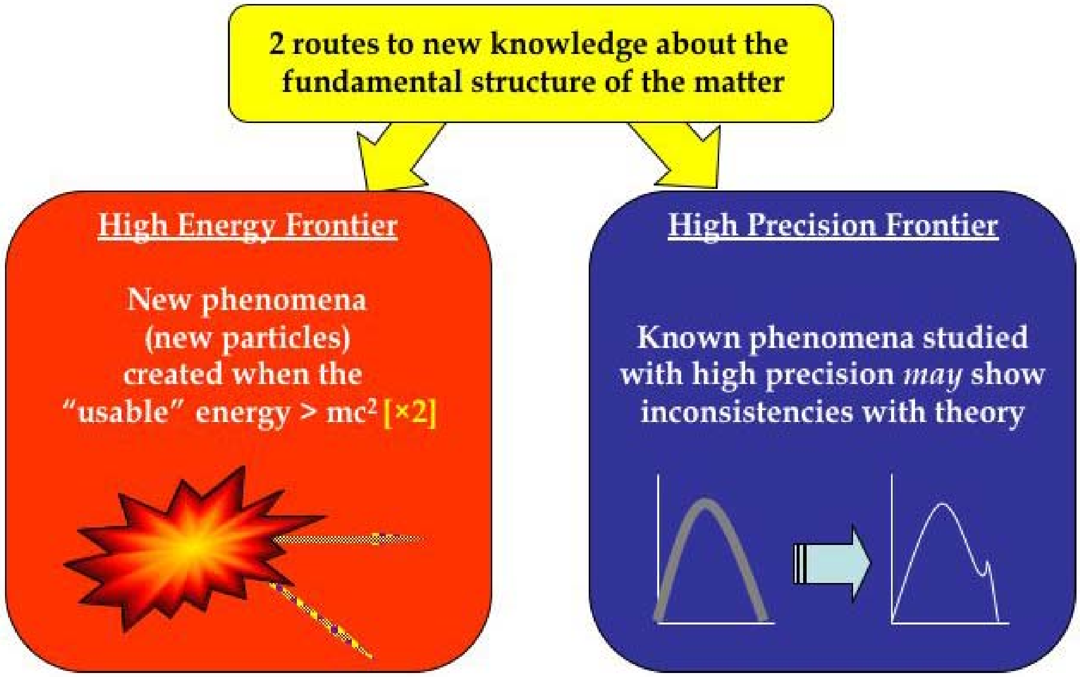

Fig. 1. High-energy physics two routes to discovery.

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 superconducting 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.

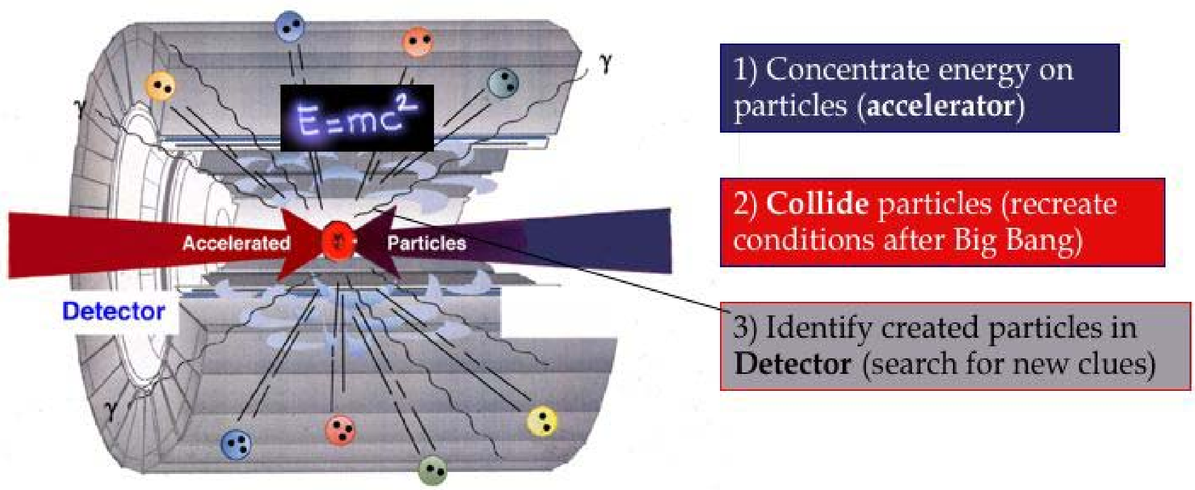

Fig. 2. Function of a particle and radiation detector.

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 experiments 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.

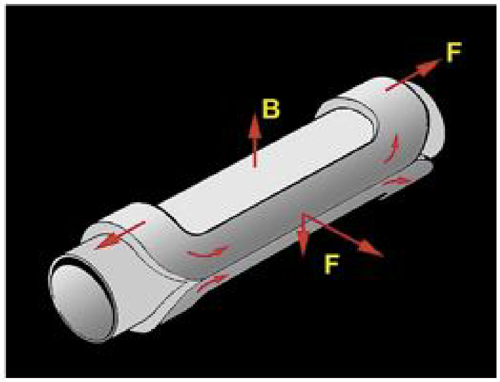

Fig. 4. Basic shape of a dipole coil. Forces on the winding, *F*, are indicated by arrows.

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.

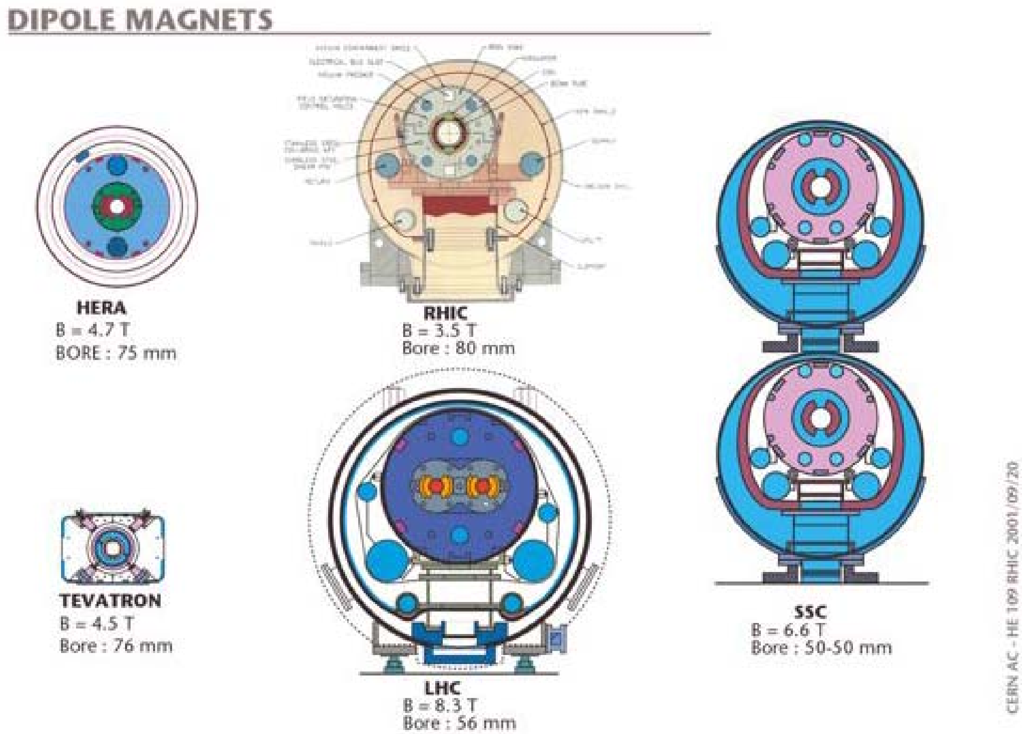

Fig. 5. The historical comparison of dipole sections in main HEP projects based on SC magnets.

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.

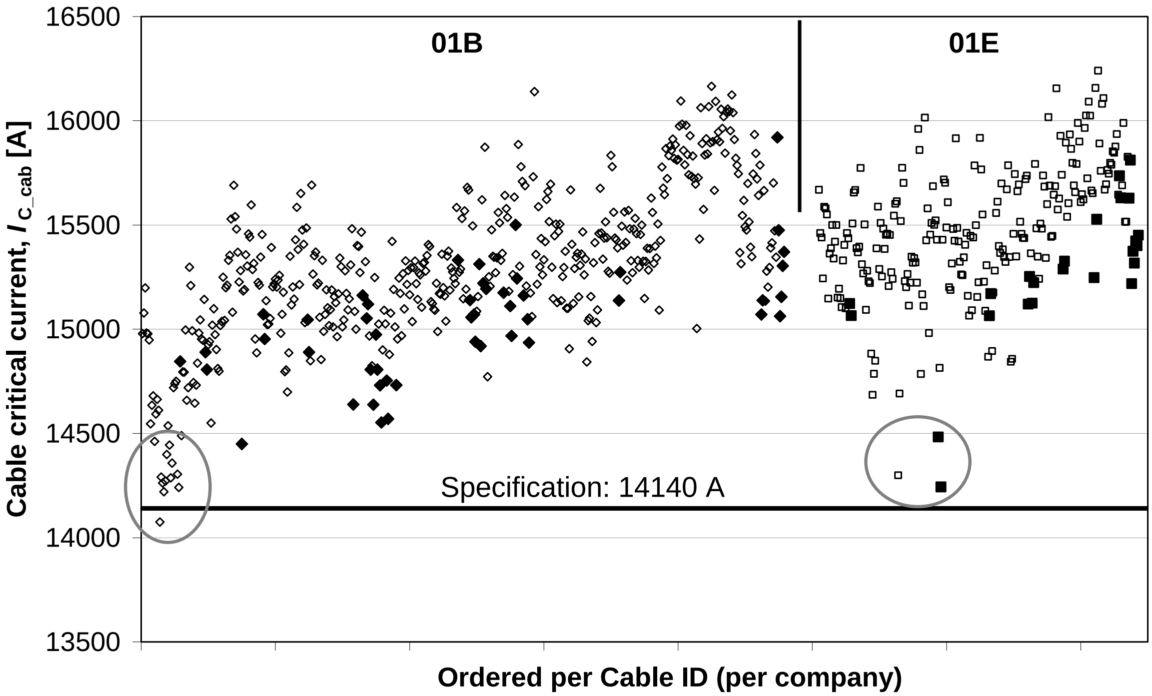

Fig. 6. Critical current measured on cable type 01 (from two companies here indicated as B and E) for the whole production. Empty symbols refers to measurements done in BNL-USA, solid symbols in CERN.

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).