Particle Accelerator and Cuprate Superconductor

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Abstract

Cuprate superconductors entered into operation at the CERN LHC, the largest particle accelerator, in 2008, as part of the current leads system, a mere 20 years after the discovery by A. Mueller and G. Bednorz. The utilization of HTS for accelerator magnets faces exceptionally demanding, as yet unresolved, challenges. However, the forthcoming generation of accelerators, necessitating high magnetic field strengths (above 15 T) and emphasizing sustainability by reducing energy consumption, presents a distinct opportunity for cuprate superconductors to emerge as the fundamental framework for all future large accelerators in high-energy physics.

Introduction

For this memorial issue in honor of Alex Mueller, whose discovery with Georg Bednorz of high-temperature superconductivity (HTS) changed the world of physics, my focus is on the role of superconductivity in the advancement of high-energy physics accelerators. Additionally, I will underscore the exceptional potential for cuprate compounds to assume a central role in the future development of very large accelerators.

Particle accelerators were conceived nearly a century ago to deconstruct matter into its fundamental constituents. Beyond serving as the most precise microscope available (for example, the LHC attains a spatial resolution of about 50 zm, which is twenty billion times smaller than the scale used in nanotechnology), accelerators methodically recreate the conditions of matter and energy density that prevailed shortly after the Big Bang. Within the LHC, we can delve into the universe's state up to 10^{-12} seconds after the Big Bang [1,2].

Superconductivity has played a crucial role in increasing the energy capabilities of high-energy physics (HEP) accelerators, for example by providing powerful magnets to bend highly rigid beams. In the case of large circular accelerators such as the Tevatron or LHC, the energy scales as follows: $E \approx 0.3 \cdot B \cdot R$, where B is the field in the dipoles (in tesla, T), R is the bending radius (in kilometers, km), and E is the beam energy measured in teraelectron volts (TeV). This explains the drive for gigantism in size that has accompanied the development of high-energy physics, fueled by the continuous pursuit of higher beam energy. The advent of superconductivity, enabling high magnetic fields while containing the race towards larger sizes, has led to the current largest accelerator, the LHC, which is a ring with a circumference of 27 km. Superconductivity has been the dominant technology in HEP and nuclear physics for at least 30 years.

However, this advantage comes with significant drawbacks. For example, the need of large cryogenic systems at low temperatures is certainly a major challenge, as it is the issue of critical current at high field and of stress management in the superconducting coils. The advent of HTS for future accelerators, can enable higher field magnets with simpler and less energy-consuming cooling plants: the challenges of next generation accelerator magnets [3,4] can be then turned into opportunities for HTS.

Accelerator magnets and superconductivity

The coils of dipole magnets used in existing HEP accelerators are typically arranged to generate a uniform field along their length, with characteristic saddle-shaped coil ends that create an opening for beam entrance (see Figure 1, left). In the cross-section perpendicular to the beam trajectory, the required uniform transverse field is generated by an arrangement of the current, in circular shells, as shown in the actual LHC magnet cross-section in Figure 1 right.

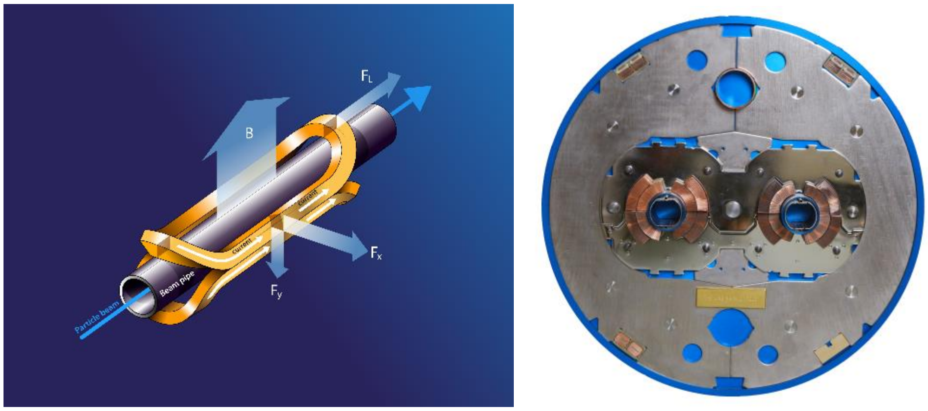

Figure 1. Left: Schematic 3D view of a single aperture dipole with beam direction (blue arrow) and current flow (white arrows in the orange coils). Right: Picture of a cross section of a real two aperture LHC dipole col mass, showing the typical shell shape of the two coil layers surrounding the beam pipe.

The central field as $B \propto J_0 \Delta a$, where J_0 is the current density and Δa is the thickness of the coil package. Clearly, the higher the current density, the higher the field. Additionally, the coil volume increases faster than the field level. In other words, the current density is the most crucial parameter for accelerator magnets. That's why in accelerator magnets, that operates at higher current densities than other types of magnets, superconductivity is confined to a small circular crust surrounding the beam pipe, as shown in Figure 1 right. which becomes hardly visible when considering the entire cryostat system.

The advantages of superconductivity are apparent from the preceding discussions. To underscore these benefits, it is worth mentioning that had the LHC been constructed with 2 T resistive magnets, it would have demanded a 100 km tunnel (leading to a substantial increase in costs) and necessitated a 900 MW power supply – over 20 times the 40 MW required by the LHC's cryogenic system. Such a power requirement would have imposed an unacceptable financial burden and environmental impact.

The main characteristics of accelerator magnets are:

1. High overall current critical density ($J_{overall}$): As discussed earlier, this is the crucial feature and HTS offers larger current densities than classical (LTS) superconductor for field above 14 T.

2. External system for force support: dipoles, like toroids, require external support to counteract electromagnetic forces (see Figure 1 left). The force-supporting system for accelerator magnets must be located outside the coils to avoid diluting the current density, therefore the superconductor should be able to withstand the accumulated external pressure
3. Minimal stability margin: This arises due to the elevated $J_{overall}$ and results in narrow stability margins, usually on the order of a few millijoules or less for low-Tc superconductors, leading to pronounced training characteristics. Cuprate superconductors, characterized by a wide temperature margin, provide a distinct advantage by significantly expanding the stability margin by nearly three orders of magnitude. This reduction in the likelihood of quench occurrences is substantial. It can be speculated that an accelerator magnet utilizing HTS may eliminate the need for training.
4. Protection through active heaters and bypass diodes: to avoid dangerous hot spot temperatures despite the enormous J_{Cu} (approximately 1000 A/mm^2) after a quench, active heaters and bypass diodes are used to rapidly cut the current within a short time span (100-500 ms). This necessitates multi-kAmps cables to maintain low inductance. The enormous stability margin, above discussed, makes external heaters less effective for quench protection for HTS than it is for LTS.
5. Field quality: the magnetic field must be controlled at about 10 ppm level over the whole magnet bore, requiring each conductor to be positioned within ±50 µm or better. Moreover, during low-field and ramp-up phases of the acceleration cycle, the management of persistent currents and coupling currents within the cable's inter-strand resistance is essential. Overcoming the challenge of controlling magnetization, as achieved with the implementation of remarkably fine filaments with a diameter of 6 µm in LHC Nb-Ti cables, is likely to be among the most intricate tasks in the application of HTS tapes for accelerator magnets.

Figure 2 provides an artistic representation of a 15 m long LHC main dipole, illustrating some of the complexity of the magnetic system, including the 1.9 K cryostat. Further details on the LHC magnet design, construction, and operation can be found in [5].

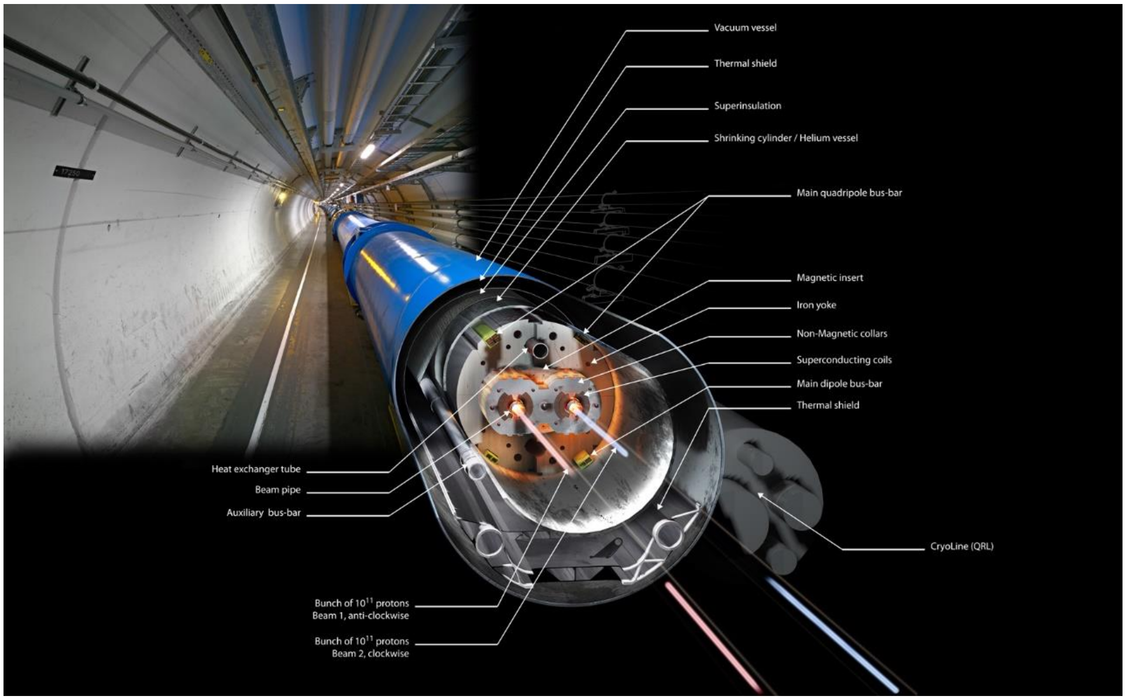

Figure 2. Artistic view of an LHC dipole in the tunnel. CERN archives.

HTS in LHC and High Luminosity LHC

LHC current leads

The LHC has also been one of the first large-scale applications of high-temperature superconductors (HTS), although in the form of short tapes and operating at almost zero field. To power the circuits of the LHC superconducting magnets, approximately 3 MA of electrical current needs to be injected from room temperature to the cold part of the circuits. The superconducting circuits are numerous, requiring a total of 1074 current leads based on HTS with various amperage ratings, distributed in different locations around the entire ring.

To minimize heat load at cryogenic temperatures, current leads rated at currents higher than 120 A utilize HTS material, specifically Bi-2223 tapes stabilized with an Ag-Au alloy. This configuration drastically reduces thermal conduction into the helium (He) bath. The design of the leads relies on the availability of a large quantity of helium gas at 5-20 K, which creates a heat sink at 50 K in the lower part of the copper section of the current leads.

From 50 K down to 4.5 K, multiple stacks of Bi-2223 tapes carry the current to the Nb-Ti/Cu bus-bars that eventually supply the superconducting magnets. A total of 1074 HTS current leads have been manufactured, including 32 pairs rated at 13 kA. More than 10,000 stacks have been assembled at CERN using a successful manufacturing process of 31 km of Bi-2223 tape by AMSC and EHTS (now Bruker). Each stack has undergone individual testing at liquid nitrogen temperature before being brazed into the main body of the lead.

The HTS current leads have proven to be robust and reliable components of the LHC superconducting circuit, operating without any serious issues for almost 15 years. An overview of the system and its operational performance is provided in [6,7].

The High Luminosity LHC powering system

The High Luminosity LHC project is a major upgrade of the LHC, which involves a complete renovation of the magnetic system in the high luminosity insertions: LHC P1, where the ATLAS Experiment is located, and LHC P5, where the CMS Experiment is installed [8].

The electrical power converters (EPC) for the new magnets in the High Luminosity LHC cannot be accommodated within the existing LHC service galleries and alcoves. Aside from space constraints, the radiation field in those regions will increase by a factor of five to seven, directly proportional to the luminosity. Consequently, the new EPCs will be installed in galleries located approximately 10-15 m away from the LHC tunnel. A novel technology based on Superconducting Links [9,10] will be employed for the electrical connection between the magnets and the EPCs, allowing the transmission of electrical current from the room temperature EPCs to the 2 K superconducting magnets.

Several cables, made from ex-situ MgB_2 superconducting wire, are assembled together in a single large cable called a link. Each individual cable feeds one circuit, resulting in different amperage and size for each cable. The base of the cable is a 1 mm diameter MgB_2 wire, consisting of 37 MgB_2 filaments with an average diameter of 50-55 µm. Each cable is electrically insulated and twisted together with other cables to form a multi-cable assembly, the link. Each multi-cable assembly is placed inside a single-unit flexible cryostat, consisting of two concentric corrugated pipes, which provides the cryogenic environment with proper thermal insulation for the cables. The multi-cable assembly is cooled by the forced flow of helium gas and has an external diameter of about 90 mm. The MgB_2 cable is then connected to a cable in HTS, made out of various 4 mm wide tapes, wrapped around a flexible central cable of copper for stabilization. The largest Superconducting Link is designed to handle a total DC current up to 120 kA at 20 K. The HTS cable has the function to carry that current from the 20 K of the MgB_2 cable up to the 50-60 K temperature of the low temperature end of the gas cooled cooper current lead. Figure 3 shows the successful first operation of a 60 m long prototype flexible MgB_2/HTS link with a prototype of the interface box (called DFH) that accommodates the large current leads and include the HTS connection between the copper section of the current lead and the MgB_2 cables. The conductor exhibits a very high degree of stability due to a large margin (10 K) at a relatively high operating temperature and the cable is designed to limit the maximum hot spot temperature to 60 K following a transition of the cable, to minimize the cool-down time of the Superconducting Links after a quench, which is a prerequisite to ensure the operation of the link is almost "transparent" to the magnet operation in the accelerators.

Figure 3. Short prototype of the High Luminosity LHC Superconducting Link system during first operation at CERN. Courtesy Amalia Ballarino (CERN).

Future Colliders

High Luminosity LHC (HL-LHC)

In Europe, at CERN, the LHC will undergo a significant modification with a new configuration called the High Luminosity LHC (HL-LHC) [11,12], already mentioned in the previous paragraph for the Superconducting Links. The HL-LHC is an upgrade of the LHC that aims to increase the collision rate by a factor of 7, with the ultimate goal of achieving an integrated luminosity of more than 4000 fb^{-1}. Several magnets have been studied and developed specifically for the HL-LHC. The central element of the upgrade is the new Inner Triplet (IT), which consists of large-aperture quadrupoles designed to reach a peak field on the coils of 11.4 T. This exceeds the capabilities of the LHC's Nb-Ti magnets, which can reach up to 8.3 T, necessitating the use of Nb_3Sn technology, a novelty for accelerators [13,14].

The development of the HL-LHC conductor was carried in 2005-2015, a time when the HTS technology was not yet matured for accelerator magnets. Therefore it was focused on two Nb_3Sn, namely Restacked Rod Process (RRP) and Internal Tin Diffusion (ITD) [15]. RRP was ultimately chosen for production, with the aim of producing unit lengths of strands well above one kilometer. Approximately 20 tons of Nb_3Sn strands have been produced for the HL-LHC IT quadrupoles.

After ten years of research and development, the production of IT quadrupoles for the HL-LHC began in 2019-2020. The initial R&D phase, based on 1 m-long full cross-section models, was quite successful. However, the extrapolation to longer magnets (4.2 m and 7.2 m for the US and CERN, respectively) proved more challenging than expected, especially for the 7.2 m version. The brittleness of Nb_3Sn, coupled with a new technology that has not been fully mastered, introduced subtle differences between the short models and full-size magnets. To compare, reproducing the results from a 1 m long model to a full-size LHC Nb-Ti magnet, initially 10 m and then 15 m long, presented fewer difficulties. In the past 3-4 years, the community has learned how to cope with the increased length, and recent results from both the US and CERN demonstrate that HL-LHC IT quadrupoles are well on track for production and installation (2026-2027). Despite the project's success, the insights derived from the initial production of HL-LHC Nb_3Sn magnets have underscored the tangible drawbacks associated with the brittle nature of Nb_3Sn wires, which poses genuine challenges for magnets intended for substantial future undertakings. These limitations serve as an additional rationale for contemplating the adoption of HTS, either as a complement or as a substitute for Nb_3Sn, in the construction of next-generation accelerator magnets.

Future Hadron Collider Projects for after LHC/HL-LHC era

Here, we will provide a brief overview of some of the upcoming large accelerator projects, illustrated in sketch of Figure 4. For a comprehensive review, refer to [16].

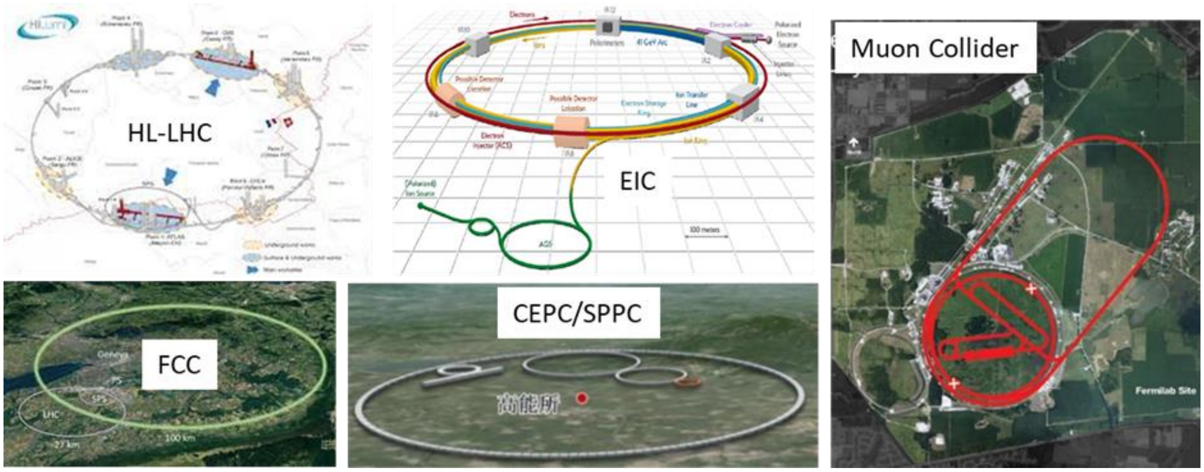

Figure 4. Layout of the future facilities entering in function within 2030 (HL-LHC, CERN), or slightly after (EIC, BNL) or beyond the next decade: FCC@CERN), CEPC/SPPC@China and Muon Collider in site not decided (FNAL site is shown as example). From [16].

In the USA, the Electron-Ion Collider (EIC) project began in 2020 and is scheduled to be built at BNL over the next 10-15 years. It is a major nuclear physics facility and a U.S. effort with some worldwide in-kind contributions. Most of magnets are in Nb-Ti, given the relatively modest field level (below 10 T).

The Future Circular Collider (FCC) proposed by CERN [17] follows a similar process to the LEP/LHC plan. It begins with the FCC-ee, a 100 km lepton (e+e-) collider with c.o.m. energies ranging from 90 to 350 GeV, designed to probe the properties of the Z, W, and H bosons, as well as the top quark with high precision. The main magnets of FCC-ee are foreseen in simple iron-dominated copper wound magnets. However, considerations related to energy efficiency are pushing the project to explore the incorporation of HTS in a significant number of corrector magnets [18]. This undertaking would necessitate around 20,000 km of HTS tape. Following the lepton collider, the FCC-hh, a hadron machine in the same tunnel, is proposed to push the energy frontier beyond the capabilities of the LHC. Operating at an impressive magnetic field strength of 16 T, the FCC-hh has the potential to achieve a center-of-mass energy of 100 TeV through proton-proton collisions. Considering the mechanical limitations of Nb_3Sn in accelerator magnets, the use of HTS becomes particularly intriguing at 16 T. An alternative approach for FCC-hh involves employing a 20 T dipole field to attain even higher collision energies. The implementation of HTS magnets for FCC-hh would demand an enormous quantity of tapes, ranging from 200,000 to 500,000 kilometers depending on the specific magnet configuration.

The Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS) has a similar proposal for lepton and hadron machines [19], which consists of two steps. The Circular Electron-Positron Collider (CEPC) would collide leptons (electron-positrons) for precision physics in the c.o.m. energy range of 90-240 GeV. It would be followed by the Super Proton-Proton Collider (SPPC) installed in the same tunnel, which would collide high-energy hadrons in the c.o.m. energy range of 75 TeV (first step with 12 T dipoles) to 125-150 TeV (ultimate step, with 24 T dipoles with iron-base superconductors).

Finally we consider the Muon Collider (MC), which occupies a unique place in the panorama of lepton colliders renowned for precision physics, and hadron colliders, engines for discovery. Muons are leptons, point-like particles suitable for precision physics. With a mass more than 200 times larger than that of electrons, muons can be accelerated to energies of even 10 TeV in a circular manner using methods, processes, and technologies already developed for proton colliders. However, muons are unstable particles, and the challenge is to complete the entire cycle from production to collision through cooling and acceleration within their 2.2 µs lifetime. The U.S. Muon Accelerator Program has produced a detailed study of a muon collider at a c.o.m. energy of 3 TeV [20]. Currently, ongoing efforts, led by the renewed International Muon Collider Collaboration under the auspices of CERN, are directing their attention toward the pursuit of higher center-of-mass (c.o.m.) energies, notably targeting the ambitious threshold of 10 TeV. This endeavor receives bolstering support from a European initiative named HE-MuCol [21]. In these recent designs, an extensive deployment of high-temperature superconducting (HTS) magnets is envisaged, particularly for the solenoids responsible for generating and cooling muons – a collection encompassing around 200 magnets of varying sizes, spanning the spectrum from 5 to 60 T magnetic fields. Additionally, there exists a potential employment of HTS technology for the main ring's 12 T dipoles, which are a key component of the 11 km long circular track. A notable advantage exhibited by the Muon Collider's magnet system, in contrast to the FCC-hh and SPPC configurations, is that all superconducting magnets function in a steady-state mode, a characteristic that significantly favors HTS application. To accommodate these ambitious plans, the projected requirement ranges between 50,000 and 200,000 strands of HTS tape, each measuring 4 mm in width, making it an essential component for realizing such an advanced machine.

The challenges for HTS in future accelerators

As previously mentioned HTS (High-Temperature Superconductors) are expected to play a major role in next-generation accelerator magnets. However, HTS technology for accelerators is still in its early stages, and various laboratories are working on overcoming basic issues rather than achieving record fields that may not be suitable for accelerators.

Among the basic issues to be studied and solved for REBCO (Rare Earth Barium Copper Oxide) HTS, which is the most investigated material for accelerators, are:

1. Adapting a highly anisotropic conductor, such as a thin wide tape, to windings that require sharp bending in all directions and ensuring acceptable field quality during field ramp-up.
2. Dealing with the long detection time of a quench, which poses challenges for magnet protection. Exploring non-insulated coil designs can be the solution to protection issues, although this presents formidable challenges for controlling the field during ramp-up and for managing current during a quench.

3. Managing the presence of single severe weak points and extensive lengths with lower performance, using joints for avoiding expensive pre-selection of top quality material.
4. Ensuring long-term stability of the material and coil performance following multiple cooling/warming cycles, powering cycles, quench events, and long storage in normal atmospheric conditions.

Many laboratories are actively investigating both Nb_3Sn and HTS for high-field accelerator magnets and efforts have also been dedicated to hybrid concepts, combining Nb_3Sn and HTS magnets with conductor grading. While this hybrid solution is attractive for cost savings, being the cost of HTS still 3-5 times higher than Nb_3Sn, it presents design challenges due to the different properties of the two technologies. Moreover, the hybrid concept inhibits one of the potential advantages of HTS, which is the ability to operate magnets at temperatures well above the boiling point of liquid helium, such as 10 or 20 K. Operating at 20 K, for example, could result in significant cryogenic power savings, such as about 200 MW for the planned FCC-hh machine (designed for operation at 1.9 K by means of HEII), greatly contributing to sustainability goals.

In Europe, an initial foray into development of HTS accelerator dipoles was based on use of Roebel cable, producing a 40 mm bore dipole, see Figure 5, that reached the 4.5 T in 2019 [22]. In the present day, the European initiative for crafting accelerator magnets in the context of next-generation colliders has expanded significantly, helmed by CERN [23], and include a considerable effort also for HTS, beside Nb_3Sn. A similar program, with a slightly different structure, is being carried out in the USA through the Magnet Development Program (MDP), which was established by the US DOE Office of High Energy Physics in 2015 [24].

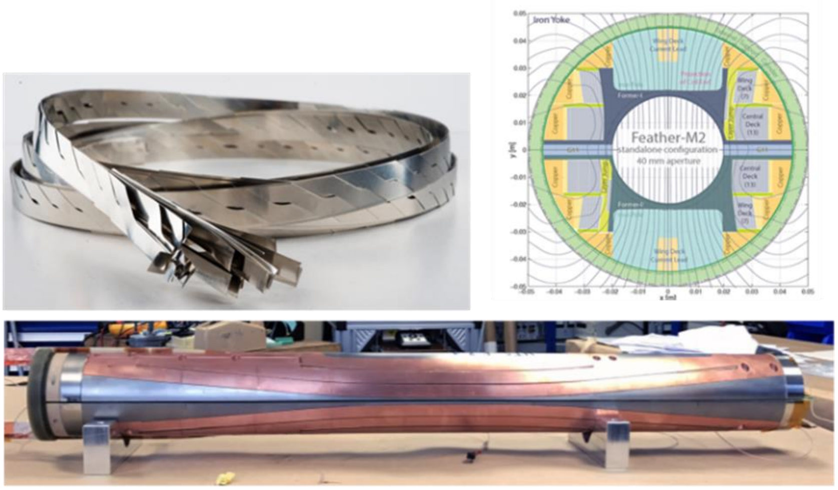

Figure 5. Various phase of the FP7-Eucard2 collaboration HTS dipole: Robel cable (top left), design of the cross section of the aligned block dipole (top right) and dipole coil after assembly before inserting in the iron yoke for testing (bottom).

Alex Muller and CERN: a personal touch

The fundamental discovery of high-temperature superconductivity by Alex Muller and George Bednorz in 1986 had a significant impact on the world of accelerators. During that time, there was a battle between two giants: the LHC at CERN and the much larger SSC (Superconducting Super Collider) in Texas. Both projects, based on Nb-Ti technology, faced the question of whether it was worth pursuing the "old" Nb-Ti superconductor, which required scarce and expensive liquid helium (LHe) or even precious superfluid helium (HEII), when a new class of superconductors promising superconductivity at higher temperatures with simple liquid nitrogen refrigeration was emerging. Fortunately, realism prevailed, and it was decided to continue with the existing practical superconductor. In 2008, the largest superconductivity project, the LHC, was successfully completed based on classical Nb-Ti superconductor.

However, HTS entered the LHC in the form of short Bi-2223 tapes for an important ancillary system: the current leads, as described in the paper. This marked perhaps the first large-scale application of HTS in the accelerator field.

In 2011, on the occasion of the centennial of superconductivity, I organized a symposium on "The roots of the LHC technology: CERN Centennial Superconductivity Symposium". The symposium, held in the CERN Council Chamber on December 8, 2011, had Prof. Alex Muller as the guest of honor. He highlighted the strong connections between the theory of superconductivity and the theory that eventually became the Higgs field, citing the important works of CERN DG Viktor Weisskopf on the Cooper pair and the nature of supercurrent [25]. It was also memorable to hear the comparison between the time it took for the discovery of classical superconductors to be applied (around 50 years) and the relatively short time it took for cuprate superconductors: 1986 discovery to 2008 LHC commissioning. It was a privilege to show Prof. Muller around CERN's infrastructure and equipment, which are largely dominated by the phenomenon of superconductivity to which he has dedicated a significant part of his scientific life. I remember his contagious enthusiasm in asking when we could build magnets with cuprates. This paper is, in a way, a belated answer: yes, finally, the time has come for HTS, even for the most demanding application - accelerator magnets!

After the symposium, we celebrated the event with a generous dinner on the Jura mountain, half an hour from CERN. I would like to conclude by sharing the picture of the event, as shown in Figure 6. This was the last time Prof. Muller visited CERN, as his health conditions prevented him from participating in the EUCAS conference organized at CERN in 2017.

Figure 6. - Prof. Alex Mueller (center) at the dinner following the "The roots of the LHC technology: CERN Centennial Superconductivity Symposium". From left to right: H. ten Kate, H. Padamsee, R. Saban, L. Rossi, S. Meyers, A. Mueller, L. Bottura, F. Bordry, Ph. Lebrun, Ms Wilson and M. Wilson, S. Bertolucci.)

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