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Development of superconducting links for the Large Hadron Collider machine

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Development of superconducting links for the Large Hadron Collider machine

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Abstract
In the framework of the upgrade of the Large Hadron Collider (LHC) machine, new superconducting lines are being developed for the feeding of the LHC magnets. The proposed electrical layout envisages the location of the power converters in surface buildings, and the transfer of the current from the surface to the LHC tunnel, where the magnets are located, via superconducting links containing tens of cables feeding different circuits and transferring altogether more than 150 kA. Depending on the location, the links will have a length ranging from 300 m to 500 m, and they will span a vertical distance of about 80 m. An overview of the R&D program that has been launched by CERN is presented, with special attention to the development of novel types of cables made from MgB_2 and high temperature superconductors (Bi-2223 and REBCO) and to the results of the tests performed on prototype links. Plans for future activities are presented, together with a timeline for potential future integration in the LHC machine.

Keywords: superconducting lines, HTS cables, MgB_2, BSCCO, REBCO, LHC powering

(Some figures may appear in colour only in the online journal)

1. Introduction

The electrical feeding of the approximately 1700 Large Hadron Collider (LHC) superconducting (SC) circuits requires the transfer of more than 3 MA of current from the power converters to the magnets. This is achieved via conventional copper cables for the room temperature path between power converters and current leads, high temperature superconducting (HTS) or resistive current leads for the transfer to the 4.5 K liquid helium bath, and Nb–Ti bus-bars operated in liquid helium at 4.5 or 1.9 K and making the connection to the SC magnets. In the present LHC configuration, power converters and current leads are both located in underground areas, the first mainly in alcoves, parallel to the machine tunnel, and the second in cryostats which are near the LHC interaction points (figure 1) and in line with the SC magnets. From each of the eight interaction points, power converters and leads feed the magnets occupying half of the two adjacent machine sectors. All equipment in the tunnel is exposed to significant levels of radiation.

For the High-Luminosity upgrade of the LHC machine [1, 2], novel superconducting lines (hereafter called ‘links’) are being developed for feeding the LHC magnets from remote distance [3]. The new electrical layout envisages the location of the power converters and of the current leads either in surface buildings or in underground areas over five hundred meters away from the tunnel, and the transfer of the current to the magnets is performed via SC links containing tens of cables feeding different circuits and transferring altogether more than 150 kA. The benefits of this remote powering via SC lines are several and can be summarized as follows:

(1) Location of the LHC power converters in radiation-free areas with a definitive solution to the problem associated with the radiation damage of these devices. As already experienced during the first years of LHC operation, events that result stochastically from single interactions between energetic ionizing particles and electronic components—single event effects—at some locations in the tunnel affect the performance of the power converters and induce failures that impact on beam availability for physics.
(2) Access of personnel for maintenance, tests and interventions on power converters and current leads in radiation-free areas, in accordance with the CERN principle of

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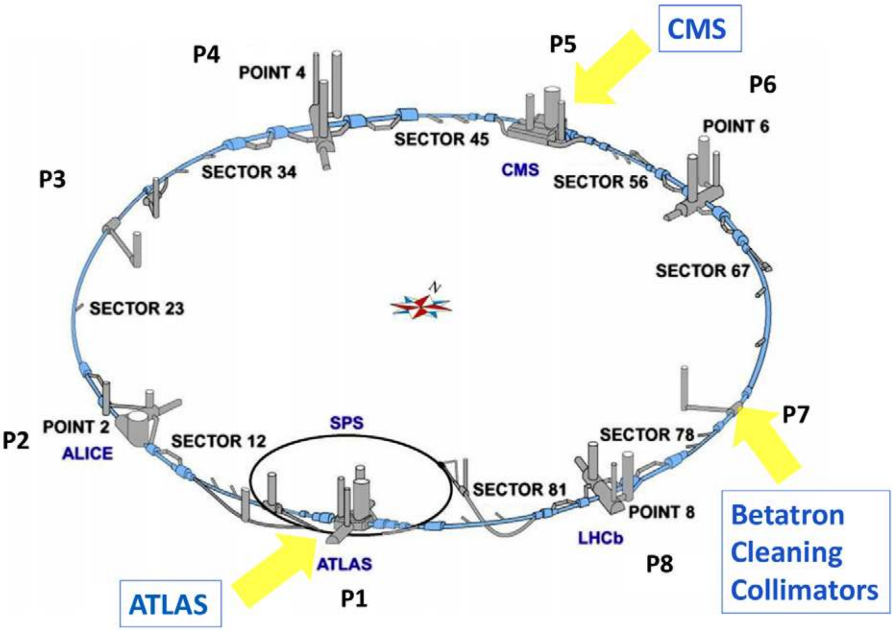

Figure 1. Layout of LHC indicating the eight LHC sectors, each located between two interaction points, and the locations where the superconducting links are planned to be integrated: near the interaction points 1 (P1) and 5 (P5), which house the high-luminosity experiments ATLAS and CMS, and near point 7 (P7), where the betatron cleaning collimation system is located.

radiation protection that optimizes doses to personnel exposed to radiation by keeping them as low as reasonably achievable (ALARA).

(3) Removal of the current leads and associated cryostats from the accelerator ring, thus making space available for other accelerator components.

The on-going program focuses on development of superconducting lines to be integrated at the LHC points 1 (P1), 5 (P5) and 7 (P7).

At LHC interaction points P1 and P5, where the high-luminosity experiments ATLAS and CMS are located, the proposed electrical layout envisages the installation of the power converters and current leads in surface buildings. This calls for development of superconducting lines about 300 m long, spanning across a vertical distance of 80 m and transferring a total DC current of about 150 kA (figure 2(a)). The powering of the new insertion magnets developed in the framework of the LHC High-Luminosity upgrade requires two such links per point (figure 2(b)), i.e. four in total. Also at P1 and P5, four additional links per point are being studied for the powering of magnets in the LHC matching sections and arcs.

At LHC P7, power converters and current leads are planned to be moved into an underground radiation-free gallery, which serves as access to the LHC ring (TZ76 in figure 2(c)). At P7, two superconducting links are needed (figure 2(c)). Each of them is about 500 m long and transfers a total DC current of about 30 kA. This paper reports on the status of the development of the superconducting links needed for the Hi-Luminosity upgrade of the LHC Triplets and for LHC P7.

2. Superconducting links for the LHC machine

2.1. Electrical and cryogenic configuration

In contrast with superconducting transmission lines developed for electrical power distribution, where one or a maximum of three cables are contained in the same cryogenic envelope, the links for the LHC contain tens of cables rated at different DC currents ranging from a minimum of 120 A up to a maximum of 20 kA. For LHC P1 and P5, each of the four links powering the High-Luminosity insertion magnets contains six cables rated at 20 kA, fourteen cables rated at 3 kA, four cables rated at 0.4 kA, and eighteen cables rated at 0.12 kA. The total current transferred by the assembly of these forty-two cables is 165 kA. The 20 kA cables are required for powering the low-beta insertion Nb_3Sn quadrupole magnets together with one Nb–Ti separation dipole, while the other cables feed corrector and trim circuits [4]. The link at P7 contains fifty cables rated at 600 A, all connected to correction magnet circuits.

The cable assemblies are incorporated in semi-flexible cryostats of the CRYOFLEX® type. The present baseline, which is to be confirmed through on-going integration studies, envisages integration in the LHC tunnel of the cryostat with the cable assemblies already pulled in at the surface. To limit the risks associated with high-current resistive joints operated in a helium gas environment, the cables are planned to be assembled in one single unit length with no splices between cables inside the link. The cryostat consists of four corrugated pipes and it includes an actively cooled thermal shield. The cooling of the superconducting link is provided by helium gas entering at a temperature of about 5 K and warming up along the line while absorbing the static load of the cryostat [5].

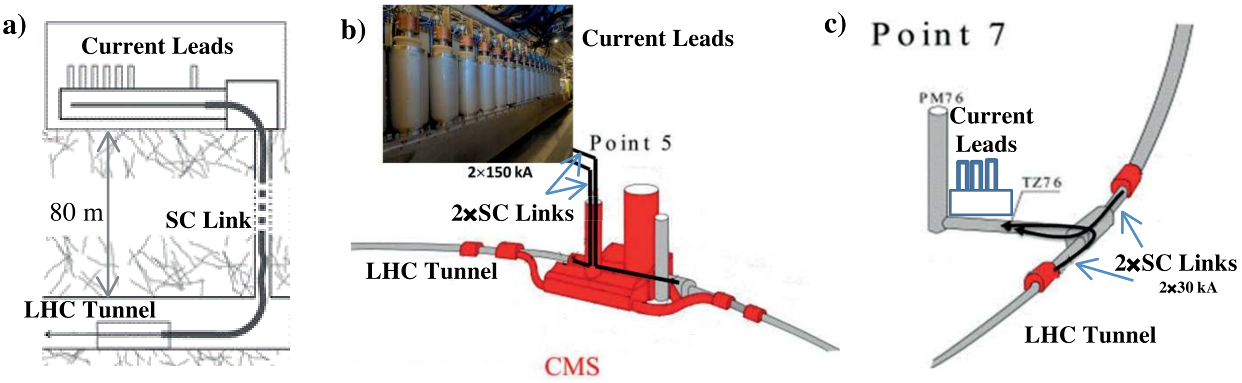

Figure 2. From left: (a) schematic layout at LHC P1 and P5, with superconducting links spanning across a vertical distance of 80 m and connecting the current leads, located in surface buildings, to the LHC magnets in the tunnel; (b) integration at LHC P5, with two superconducting links powering the insertion magnets developed in the framework of the LHC High-Luminosity upgrade; (c) layout at LHC P7, with two superconducting links in the tunnel connecting the current leads, located in an underground gallery (TZ76), to the magnets in the LHC tunnel.

The maximum operating temperature of the superconducting cables is defined to be 25 K for links containing MgB_2 cables and 35 K for links with REBCO or Bi-2223 cables. After having cooled the superconducting line, the helium is used for the cooling of the current leads and of the corresponding cryostat, and it is finally recuperated at the surface at room temperature. The whole system, i.e. the link and current leads, relies on cooling with helium gas [5].

2.2. Superconductors: MgB_2, REBCO and Bi-2223

The superconductors which are investigated for application to the superconducting link project are MgB_2, REBCO and Bi-2223. Today commercially available REBCO and Bi-2223 tapes meet the electrical requirements specified for the project, i.e. a critical current (I_c), at 35 K and in a field of 0.5 T, of above 400 A. Tapes of about 4 mm width are considered for this application. The mechanical characteristics of REBCO and Bi-2223 conductors are above the minimum specified performance, which asks for a minimum bending radius of 100 mm and critical tensile strain of 0.3%. The availability of helium at low temperature enables the use of MgB_2. The specified mechanical characteristics of the MgB_2 conductor are the same as those required for the REBCO and Bi-2223 tapes for this application. Also required current capability is the same but operation is at lower temperature, i.e. the I_c of a MgB_2 wire with a diameter of less than 1 mm is specified to be at least 400 A at 25 K and in a field of 0.5 T. REBCO, Bi-2223 and MgB_2 tapes are candidates for the links at LHC P7. MgB_2 round wire is considered for the links at LHC P1 and P5.

Long lengths of commercially available REBCO, Bi-2223 and MgB_2 tapes have been procured for production of cables at CERN. More specifically, unit lengths of 100 m of REBCO and Bi-2223 conductor and of 1 km of MgB_2 tape conductor were procured. However, from the very beginning of the project it appeared that long lengths of round MgB_2 wire with the specified characteristics were not yet available. In 2008 CERN and Columbus Superconductors entered into a collaborative R&D activity aimed at the development of suitable MgB_2 round wire. Different types of MgB_2 wires with improved characteristics were studied and produced at Columbus Superconductors [6]. This activity was accompanied by an intensive characterization program performed at CERN with the purpose of qualifying the conductor and providing feedback on performance and requirements.

The first attempts to make MgB_2 wires for the superconducting link project led to the production of a conductor (S1, figure 3(a)) with a quasi-square cross section and a width of initially 1.6 mm, and later 1.1 mm [7]. The composition of this wire was the same as that of the tape commercialized by Columbus, i.e. 12 quasi-rectangular superconducting filaments (130 – 170 μm width) were embedded in a Ni matrix, and the stabilizer was provided by a central Cu core surrounded by an Fe barrier. The filling factor of this wire was about 14%. The engineering current density measured on short samples was up to 300 A mm^{-2} at 20 K and 0.5 T, but homogeneity of critical current as measured on short samples at 4.2 K had to be improved.

With the purpose of enhancing uniformity of the wire cross section, reducing the filament size, and increasing the filling factor, a new wire (S2, figure 3(b)) with Monel matrix and quasi-trapezoidal or hexagonal superconducting filaments was produced. The filaments were surrounded by a Ni barrier, of which different thicknesses were tried. Several quasi-square wires with 12, 19, 36 or 37, 61 and 91 MgB_2 filaments were manufactured, and filling factors of about 24% were achieved. First round wires with 1.1 mm diameter and 37 superconducting filaments were produced and engineering critical current densities of up to about 550 A mm^{-2} were measured at 20 K and 0.5 T. With this first generation of wire, homogeneity of I_c, as verified on critical current measurements at 4.2 K of hundreds of short-length conductors, was not yet achieved, and premature quenches were observed on some samples. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis [8] identified the two porous and brittle MgB_2–Ni reaction layers—each about 7–10 μm thick—generated during heat treatment by chemical

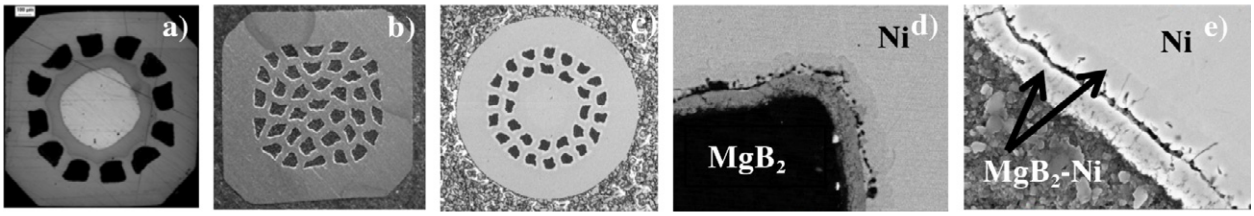

Figure 3. Different generations of MgB$_2$ Columbus round wires. From left: (a) S1 octagonal wire with nickel matrix and central copper stabilizer surrounded by iron barrier; (b) S2 quasi-square wire with Monel matrix and nickel barrier around the filaments; (c) S3 round wire with Monel matrix and niobium barrier around the filaments; (d) and (e) SEM cross section imaging of wire S2 [8]: porosity and detachment in between the two MgB$_2$–Ni reaction layers.

reaction of the wire at the interface between the superconductor and the Ni barrier (figures 3(d) and (e)) as the cause of a non-uniform current distribution among the superconducting filaments. In particular, thermo-electrical stability of some samples was found to be compromised by porosity and voids generated at the interface between the two reaction layers. Inhomogeneous current distribution among superconducting filaments at the joints and increased current-transfer length in the resistive Monel matrix were generating premature. quenches in some wires. Because of their brittle structure, the MgB$_2$–Ni reaction layers were also found to be critical for the achievement of the required mechanical properties of the wire.

In the third generation of wire (S3, figure 3(c)) the nickel was replaced with niobium as the barrier around the superconducting filaments. Round wires of 0.98 mm diameter with a Monel matrix, a Nb barrier around each MgB$_2$ filament, a Ni barrier around the Nb and a central Cu core were produced [6]. This wire has 30 superconducting filaments and a filling factor of about 10.4%. SEM analysis of several cross sections showed no merging of filaments, intact barriers and formation of a thin and uniform Nb–Ni reaction layer in between the Ni and the Nb barriers. Hundreds of short samples measured at CERN at 4.2 K showed reproducible critical current densities of about 500 A mm^{-2} at 4.2 K and 1 T [9]. The J_c at 20 K and 0.5 T measured at Columbus on short samples was 380 A mm^{-2}. The minimum bending radius of reacted wires was found to meet the specified requirements [10].

A new generation of MgB$_2$ wires with 0.85 mm diameter, having the same composition of S3, but the central Cu core suppressed and an increased number of superconducting filaments—37—is now being produced at Columbus. In this last generation of wires, the stabilizer is introduced by plating the external surface of the conductor with a copper layer a few tens of microns thick. Plating is followed by tinning of the Cu surface, with the purpose of producing a final 0.85 mm diameter strand suitable for integration in a cable having a controlled inter-strand resistance.

2.3. Superconducting cables

Concepts of cables and prototypes made from wire and from tape superconductors were developed and validated at CERN. More specifically, the tape geometry was retained for the cables in the links at P7, while MgB$_2$ round conductor was used for the cables in the links at P1 and P5.

For the links to be integrated at LHC P7, a new concept of 1 kA range HTS cable optimized for electrical transmission, and conceived for enabling the use of tape conductor (MgB$_2$, REBCO or Bi-2223) in cables, has been developed [3]. The cable, hereafter referred to as a twisted-pair, consists of two cable units that transfer the same current in opposite directions. A unit is a stack of three tapes of superconductors, interleaved with copper strips, which is electrically insulated by wrapped Polyimide tape and then twisted with a second such stack to form the twisted-pair assembly (figure 4(a)). This type of cable has been assembled at CERN using commercial MgB$_2$ (3.6 mm width, 0.67 mm thickness), REBCO (4.1 mm width, 0.095 mm thickness) and Bi-2223 (4.5 mm width, 0.36 mm thickness) tapes. The final twisted-pair assembly has an equivalent diameter varying from 5.6 to 7.2 mm and a typical twist pitch of 300 mm. The measured current capability is 1 kA per unit of the twisted-pair assembly at about 30 K for MgB$_2$ and at 60 K for REBCO and Bi-2223 [11, 12]. Two cabling machines, a static machine for assembling stacks of insulated tapes and a rotating machine for the twisting the two insulated stacks, were designed and built at CERN. These machines enable the production of long—kilometer—lengths of twisted-pair cable.

For the superconducting links to be integrated at LHC P1 and P5, where cables rated at up to 20 kA at 25 K are needed, the effort has up to now been concentrated on development and testing of prototype cables demonstrating the possibility of transferring high current with MgB$_2$ round wires [13]. High-current cables produced recently at CERN use an optimized wire (S3 in figure 3(c)) that successfully went through an extensive program of qualification measurements [9].

The 20 kA cable (figure 5(b)) consists of six sub-cable units (figure 5(a)), each made of eighteen MgB$_2$ round wires twisted around a flexible multi-strand copper core. After the successful development of MgB$_2$ round wires, a sub-cable unit about 2 m long was assembled and electrically characterized in liquid helium at 4.2 K. It reached a critical current of 10.507 kA (1 μV cm^{-1} criterion, self-field conditions) [14]. A two meter long 20 kA cable at 25 K, consisting of six sub-cable units, was also assembled and measured in liquid helium at 4.2 K. It reached the expected critical current of 30.4 kA (1 μV cm^{-1} criterion, self-field conditions) [14].

After successful qualification in liquid helium, the MgB$_2$ cables were measured at higher temperatures. Two 10 m long sub-cable units (figure 5(a)) were characterized in a

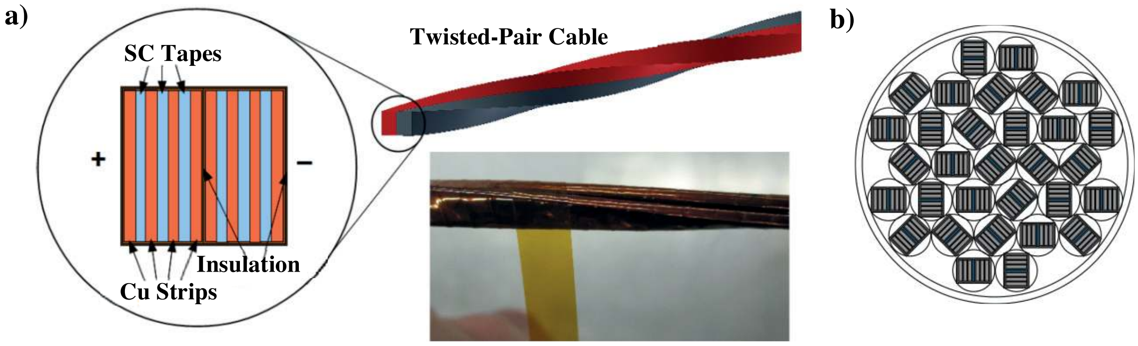

Figure 4. Cables made with superconducting tapes (Bi-2223, REBCO or MgB_2). (a) Twisted-pair cable consisting of two cables—each with three superconducting tapes and four copper strips—electrically insulated and then twisted together to form a pair; (b) cable assembly made of 31 twisted-pair cables for LHC P7.

purpose-built test station where cooling of the cables is provided by forced flow of helium gas entering at a pressure of about 1.5 bar and at temperatures that can be varied from 5 to 70 K (figure 6). The test station consists of a liquid helium bath cryostat, equipped with a pair of conventional current leads connected at their cold end to Nb–Ti cables, and of a CRYOFLEX® line, 20 m long, which houses the MgB_2 cables in the helium gas environment. The current is transferred from the leads to Nb–Ti cables, inside the liquid helium bath, and then to the two MgB_2 cables connected in series to form the go and return lines of the circuit. A purposely developed feed-through assures the separation between the liquid and the gas and provides the electrical continuity between the Nb–Ti and the MgB_2 cables. During the measurements, homogeneity of the temperature across the 10 m length of MgB_2 cables was maintained to within 1 K.

The critical current of the 10 m long MgB_2 cables was measured to be 3541 A at 27.5 K, in accordance with that calculated from the strand performance [15]. Several quenches were performed with no degradation of electrical properties. The same cables successfully transported at 20 K and in DC mode 5000 A—the maximum current at which the test station could be operated. At 20 K, the estimated critical current of the cables is 5800 A. While other groups have already reported successful development and test, at 20 K, of 10 m long 2.8 kA cables made with MgB_2 tape conductor [16], these tests represent the first reported measurements of long high-current cables assembled with reacted MgB_2 round wires. Presently an upgrade of the test station is taking place, with the objective of qualifying 20 m long cables operated at currents of up to 20 kA at 20 K and the cable assemblies needed for the superconducting links.

2.4. Superconducting links

Cables of the type described in section 2.3 are grouped together to form the cable assemblies required for the superconducting links.

Twenty-five twisted-pair cables are required for the link at LHC P7. In figure 4(b) an assembly made of thirty-one twisted-pair cables (six spare units) is reported. This assembly has an equivalent diameter ranging from 40 mm (REBCO tape) to 50 mm (MgB_2 tape). A 20 m long MgB_2 prototype has recently been assembled at CERN and qualification in nominal operating conditions will follow. In addition, tests have already been performed on a 5 m long assembly, which was fully validated and operated at nominal current [17]. The external diameter of the CRYOFLEX® semi-flexible cryostat containing the cable assembly is 163 mm.

The link at LHC P1 and P5 contains six cables rated at 20 kA, fourteen cables rated at 3 kA, four cables rated at 0.4 kA, and eighteen cables rated at 0.12 kA for a total current capacity of 165 kA (figure 5(e)). In addition to the 20 kA cables described in section 2.3, the link contains concentric and electrically insulated 3 kA cables (figure 5(c)), each made of 18 MgB_2 wires, and 0.4 and 0.12 kA (figure 5(d)) cables made of twisted copper and MgB_2 strands. The complete multi-cable assembly has an external diameter of about 65 mm and a mass of about 11 kg m^{-1}. The external diameter of the CRYOFLEX® semi-flexible cryostat containing the cable assembly is 220 mm. This link will cover 80 m of vertical distance for transferring the current from the surface down to the LHC underground areas (figure 2(a)).

3. Plans and schedule

The total quantity of superconductor required for the SC link project exceeds 1000 km. Today plans envisage integration of the SC links in the LHC accelerator during the foreseen machine shut-downs, i.e. in 2018 for the link at P7 and in 2023 for the links at P1 and P5. The integration of the links requires the removal of existing hardware and the design and integration of purpose-built interfaces to the machine. With the present schedule, procurement of conductor for series production will start in early 2015, for the system at P7, and it will continue until 2020 with completion of the procurement for P1 and P5.

4. Conclusions

Important milestones have been achieved in the development of the superconducting links for the LHC machine. In particular, system requirements from the High-Luminosity upgrade project have been defined, cables rated at above

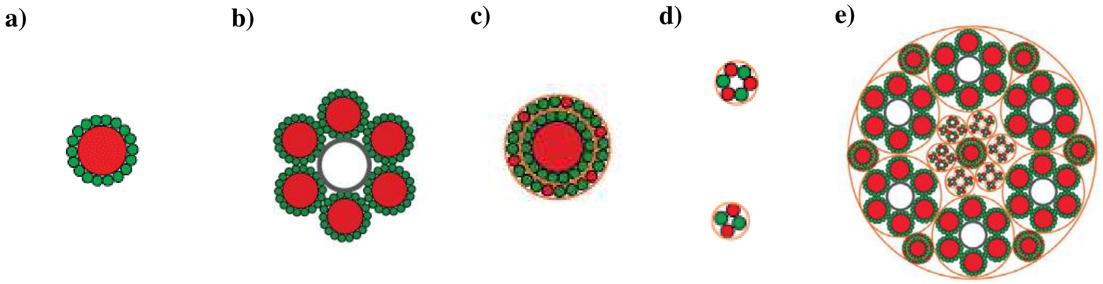

Figure 5. Cables made with MgB_2 round wire. (a) Sub-unit of 20 kA cable, $\Phi \sim 6.5$ mm ; (b) 20 kA cable, $\Phi \sim 19.5$ mm; (c) concentric 2×3 kA cable, $\Phi \sim 8.5$ mm; (d) 0.4 kA cable (top) and 0.12 kA cable (bottom), $\Phi < 3$ mm ; (e) 165 kA cable assembly for LHC P1 and P5 (6×20 kA, 7×2×3 kA, 4×0.4 kA, 18×0.12 kA), $\Phi \sim 65$ mm.

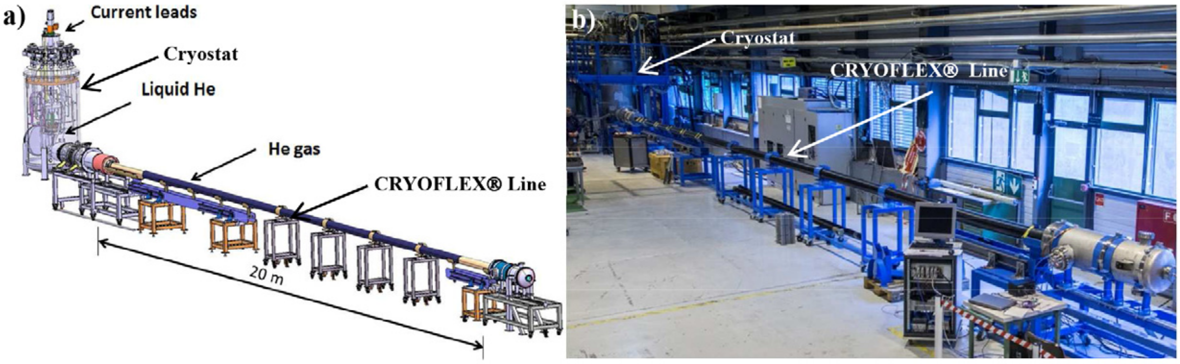

Figure 6. Test station for the measurement of REBCO, Bi-2223 and MgB_2 cables and cable assemblies at temperatures in the range from 5 K to 70 K: (a) schematic layout; (b) test station constructed and operated at CERN.

600 A at 25 K and made from REBCO, Bi-2223 and MgB_2 commercial tape conductor have been developed and validated, and a prototype superconducting link 5 m long made from 25 twisted-pair MgB_2 cables has been successfully tested in nominal operating conditions. Thanks to a collaborative effort between CERN and Columbus Superconductors, round MgB_2 wires with uniform current density and optimized for use in high-current cables have been developed and produced at Columbus. First cables made with MgB_2 reacted round wires were successfully assembled and measured at CERN, and currents of up to 30.4 kA at 4.2 K and up to 5 kA at 20 K were measured. A test station for the measurement of 20 m long cables at any temperature in the range from 5 K to 70 K and at currents of up to 20 kA was developed and commissioned at CERN. Future efforts will be focused on final development of high-current cables and multi-cable assemblies, on the system design and on integration studies in the accelerator. The quantity of superconductor required for the LHC superconducting links project—more than 1000 km in total—is such as to represent a medium-sized application of high temperature superconductors to accelerator technology.

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