COMMISSIONING AND FIRST OPERATION OF SUPERCONDUCTING LINKS AT THE LARGE HADRON COLLIDER (LHC)

R. van Weelderen[1], T. Goiffon[1], A. Perin[1], C. Darve[2], R.S. Doohan[3], S.G. Gilankar[3]

[1]CERN, European Organization for Nuclear Research,
1211 Geneva 23, Switzerland

[2]Fermi National Accelerator Laboratory,
Batavia, IL, 60510, USA

[3]Center for Advanced Technology,
P.O:CAT, Indore, Madhya Pradesh 452013, India

ABSTRACT

The Large Hadron Collider (LHC) now under commissioning at CERN is a 26.7 km collider based on several thousand high-field superconducting magnets, the majority of which operating in superfluid helium below 2 K and some isolated magnets operating in normal helium at 4.5 K. Four superconducting links (DSLs) of about 76 m in length and one of about 517 m in length, were designed, constructed and installed over a three year period. Their purpose is to transport current over long distances whenever underground LHC space constraints prevents to put power converters, current feed boxes and magnets in each others' proximity. The four 76 m long DSLs transport current between current feed boxes and several of the isolated magnets, whereas the 517 m long DSL transports current between two current feed boxes. The links are comprised of cryogenic, vacuum-insulated, transfer lines housing one or more superconducting cables. The operating temperatures are about 5 K for the DSL part that houses the cable and about 60 K for the heat shield. Their commissioning and performance results at first operational experience in the beginning of 2008 are discussed.

KEYWORDS: LHC, Low Tc superconductors, Superconducting transfer lines, Superconducting links, Applied superconductivity.

INTRODUCTION

The LHC is constructed in a 26.7 km circumference tunnel at depths varying between 50 m to 150 m. It is segmented in 8 curved sections separated by long straight sections (LSSs) with possible interaction points (IPs) for the particle beams. Underground access is provided at 4 of the 8 IPs between the machine sections [1]. Due to underground space constraints five DSLs are necessary and are to be functionally integrated into the existing LHC cryogenic system. The DSLs were designed, constructed and installed over a three year period. They were procured from and installed by an external contractor [2], according to CERN's design specifications [3]. CERN provided the superconducting cables, and managed all electrical connections, feed-throughs and electrical testing and provided expert help for detailed mechanical issues.

FUNCTIONAL DESCRIPTION

Four type-1 DSLs are of similar design, differing only in the precise mechanical layout of their routing in the LHC tunnel. They serve as superconducting current transmission lines between current feed boxes (DFBs) [4] and accelerator magnets. DC currents are in the range of 120 A to 6000 A. Their lengths are about 76 m with two intermediate branches of about 3 m. They are located at LSS 1 and 5 on either side of the IPs and connect a current feed box to the Q6, Q5 and Q4D2 magnet cryostats.

There is one type-2 DSL located around IP3. It serves as a superconducting current transmission line between two current feed boxes (DFBLC and DFBAF). It is 517 m in length without any intermediate branches. DC currents are in the range of 120 A. In addition to the current transmission function, it provides the cryogens for DFBLC. For that purpose the DSLC outlet temperature shall be at maximum 5.4 K.

The electrical connections are established by use of two types of NbTi superconductors: one of 6 kA and one of 0.6 kA current rating. The superconductors' temperatures have to be kept below 6 K. The superconductors are grouped in cables, held together by an external stainless steel braid. To protect the copper braids from cables to mutually damaging each other, several layers of protection were added (FIGURE 1). There are three cable variants, 12x0.6 kA, 3x6 kA and 48x0.6 kA. TABLE 1 summarizes the cable routing, and the approximate cable diameters.

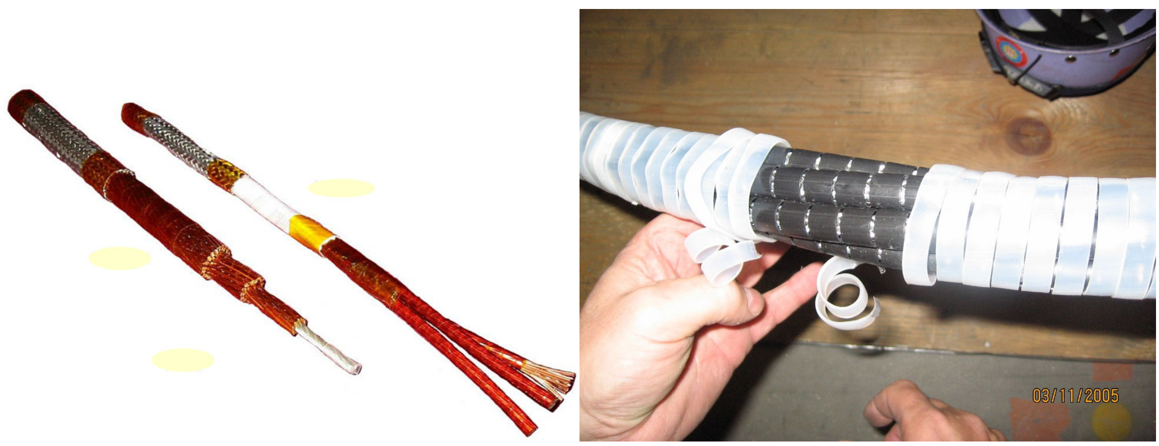

FIGURE 1. Superconducting cables, with stainless steel braid (left): 1x 600 A cable housing 48 individual conductors, 1 x 6 kA cable housing 3 individual conductors. Cable bundle with added protection (right).

TABLE 1: Type-1 & 2 DSLs, summary of cryostat powering connections

Type-1 DSL cryostats	**Number of 6 kA cables x (approximate cable Ø)**	**Number of 0.6 kA cables (approximate cable Ø)**	**Type-2 DSL cryostats**	**Number of 6 kA cables x (approximate cable Ø)**	**Number of 0.6 kA cables (approximate cable Ø)**
DFBL	4 x (12.5 mm)	1 x (11 mm)	**DFBLC**	N/A	1 x (19 mm)
Q6	1 x (12.5 mm)	N/A	**DFBAF**	N/A	1 x (19 mm)
Q5	1 x (12.5 mm)	N/A	N/A	N/A	N/A
Q4D2	2 x (12.5 mm)	1 x (11 mm)	N/A	N/A	N/A

OPERATING CONDITIONS

Both types of DSL are cryogenic, vacuum-insulated transfer lines housing one or more superconducting cables. They have active 60 K screen cooling, independent of the cooling of the superconducting cable carrying core. Sections are depicted in FIGURES 2 and 3.

The DSLs are functionally integrated into the LHC cryogenic system according to the link specific flow diagrams shown in FIGURES 4 and 5.

Active screen cooling is provided at 60 K in between 19.5 bar and 19.0 bar. The 60 K screens of the three branches of the type-1 DSL are conduction cooled from the branching-off location side. To limit the heat in-leak, these screens extend as far as possible into the branches towards the magnet cryostats, the remainder being unshielded. The type-2 DSL is actively cooled over its whole length. It is the return piping which is thermally anchored to the thermal screen in order to limit pressure drop over the 1034 m long circuit.

The cooling of the superconducting cable carrying core is accomplished with a flow of supercritical helium at a pressure of about 2.9 bar, and with temperatures in the 4.5 K to 6 K range. To assure sufficient temperature margin and to provide independence of local supply conditions the helium is pre-cooled to 4.5 K before entering the DSLs. The flow rate is regulated as function of temperature, 5.25 ± 0.75 K, at each outlet of the type-1 DSLs. The flow rate of the type-2 DSL is regulated at the inlet to the DFBLC and is a function of both the required DSL outlet temperature as well as the DFBLC helium supply requirements. The vapour is returned via a warm recovery line.

For both types of DSL the cable carrying core volume is in open connection to the supply header. From the safety point of view the type-1 DSLs are considered as an extension of the supply and no additional measures are implemented. The connection of the type-2 DSL to the supply header is relatively small compared to the cable carrying core volume. This volume therefore has a dedicated protection against over pressure. Safety discharge devices are installed at both extremities, though discharge into a dedicated cold header is favoured. The discharge will be into the cold header at the DFBAF side at 1.70 MPa absolute, and into the LHC tunnel atmosphere at the DFBLC side at 1.95 MPa absolute.

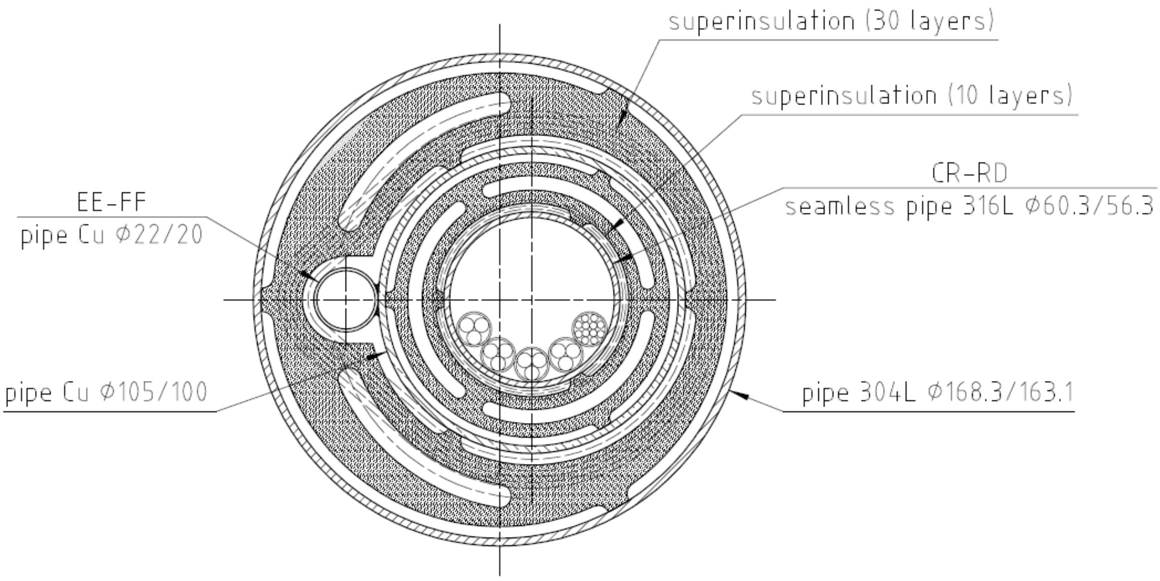

FIGURE 2. Type 1 DSL basic cross-section

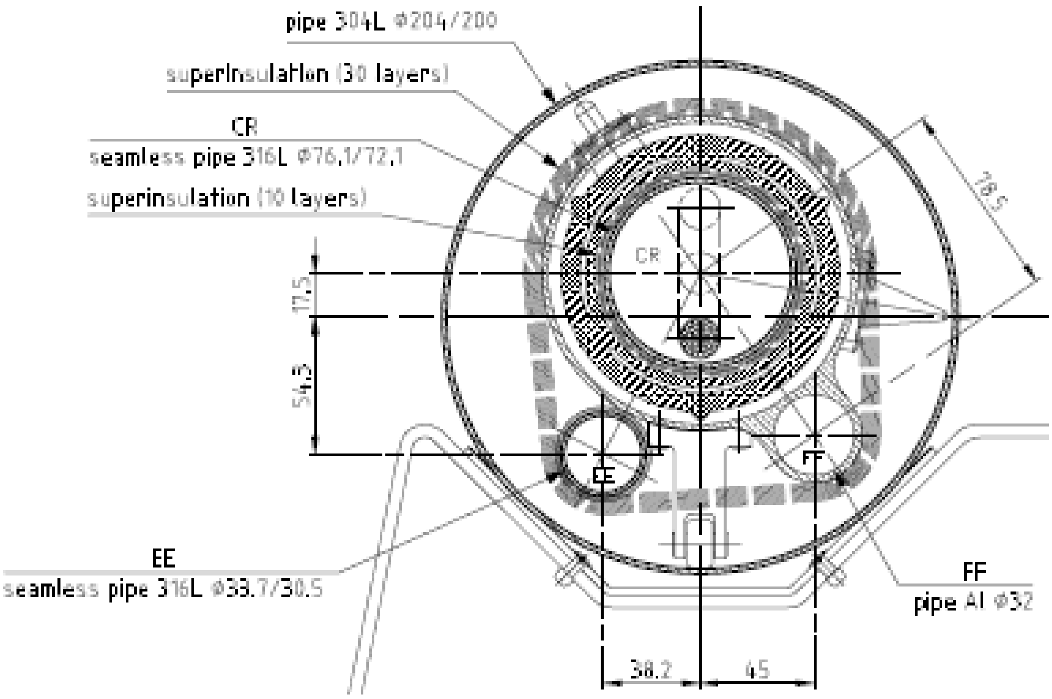

FIGURE 3. Type -2 DSL basic cross-section

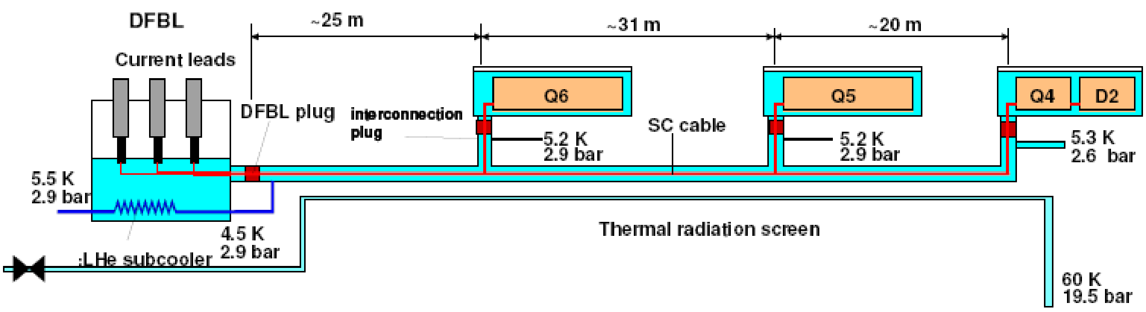

FIGURE 4. Type-1 DSL flow diagram.

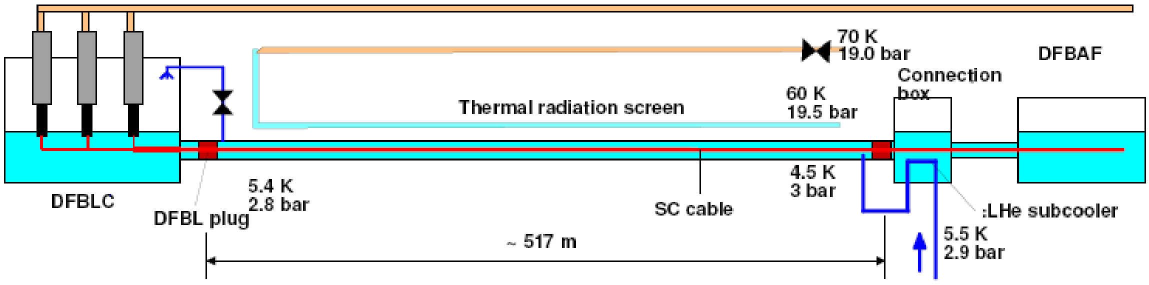

FIGURE 5. Type-2 DSL flow diagram.

MECHANICAL CHARACTERISTICS

Both DSL types are made up of straight pipe sections in order to limit heat loads and to limit space occupancy. The thermal screen and the attached thermalizing pipe are made from extruded Aluminum. Flexible sections are only used for very short lengths to resolve possible tolerance or thermal contraction issues. The DSLs allow a minimum bending curvature of 200 mm for the incorporated superconducting cables. The design pressures are 22 bar for the thermal shield lines and 20 bar for the superconducting cable lines. The cable carrying lines are separated from the current feed boxes and magnet cold masses respectively by helium tight plugs, withstanding 20 bar [5].

Type-1 DSLs have thermal contraction compensation systems at each of the interface and branching locations only. The superconducting cables running from the current feed boxes to the magnet cryostats are in one piece, and were introduced in situ into the DSL (FIGURE 6). The cables are left lying loosely inside and are held only at the thermal contraction compensation locations and at the interfaces to the DFBL and magnet cryostats.

The type-2 DSL carries only one superconducting cable which is divided into four pieces of lengths between 65 m to 170 m. The cable pieces were inserted with an over-length by slightly deforming the cable mechanically and left lying loosely inside the cable carrying DSL core. It is held only at internal thermal contraction compensation locations, every 25 m, and at the interfaces to the DFBLC and DFBAF (FIGURE 7).

COMMISSIONING AND PERFORMANCE

The commissioning proceeded according to the rhythm of the various LHC sector becoming available from end 2007 up middle of September 2008. All DSLs were electrically, pressure and leak tested in-situ during their assembly and after their connection to the LHC cryogenic system.

All four type-1 DSLs have been cooled down and the associated magnets powered. Cool-down was done slowly, in the shadow of other activities, but can in principle be done in a few hours. Temperatures are very stable, (FIGURE 8), easily within the specified allowed range of 5.25 ± 0.75 K. The system is insensitive to current ramps since the associated dynamic heat load is two orders of magnitude below the static heat lead. The static heat load is estimated based upon the enthalpy change of the helium and the corresponding mass flow. The type-1 DSLs exhibit heat loads of about 9 ± 2 W, well within the specified call for tender value of 11 W. The major uncertainty comes from the fact that the control valve characteristics have to be used for the mass flow determination.

The type-2 DSL has been cooled down for the first time in September 2008. A mass flow of about 3.6 g/s, roughly twice the specified call for tender value, was necessary to obtain 5.4 K at the DSLC outlet. Powering showed that some of the 48 superconducting wires were limited to 400 A, instead of their 600 A rating. Further investigation showed that a local extra heat load of about 15 W in a flexible portion of the DSLC, about 2 m before the outlet, perturbed the flow pattern enough to prevent proper cooling of the superconducting cable. Increasing the mass flow to 10 g/s allowed full powering up to 600 A. X-ray investigation after warm-up confirmed the hot spot due to the thermal screen and inner pipe touching each other and the room-temperature vacuum enclosure, FIGURE 9. This flexible section has been repaired, and with the hot spot eliminated we can expect the DSLC to perform close to its specification. Cool-down and powering is scheduled for the fall of 2009 and a dedicated measurement campaign will be needed to confirm the values and the dynamic behaviour in detail.

FIGURE 6. Cable bundle insertion in type-1 DSL (left), and extraction at a branch (right).

FIGURE 7. Type-2 DSL view of cable with wavy over-length pattern and clamp (left), general view of DSL at thermal compensation location (right)

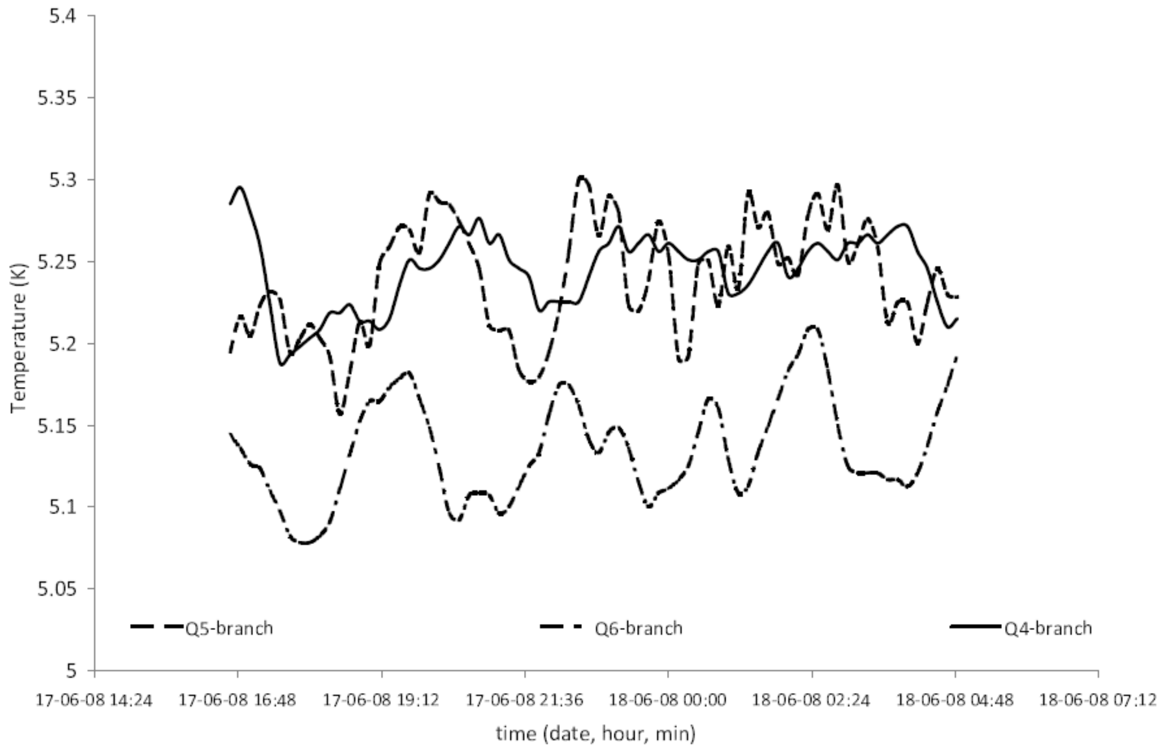

FIGURE 8. Typical type-1 DSL temperature stability.

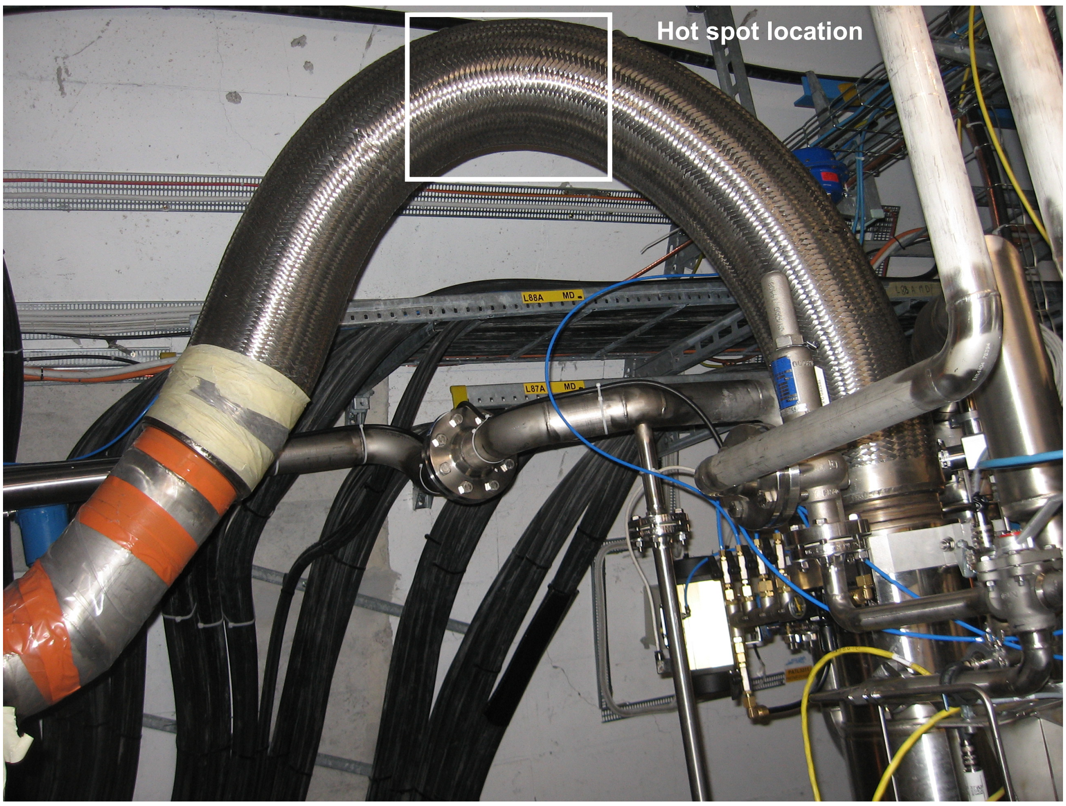

FIGURE 9. Hot spot location at top of flexible near to DSLC outlet into the DFBLC (on the right side).

CONCLUSION

Five superconducting links have been designed, built and installed using classical NbTi superconductors, covering a total length of more than 800 m. Operation of the 76 m long type links has proven to be smooth. Heat loads are as low as foreseen and temperature stability is excellent. The links have up to now shown to be a reliable part of the magnet powering chain. The 517 m record long link has been cooled down once and has apart from an identified hot spot not shown any mechanical nor cryogenic weaknesses. Its behaviour under real magnet powering conditions will be investigated in the fall of 2009.

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