

OPERATIONAL EXPERIENCE WITH THE LHC SUPERCONDUCTING LINKS AND EVALUATION OF POSSIBLE CRYOGENIC SCHEMES FOR FUTURE REMOTE POWERING OF SUPERCONDUCTING MAGNETS

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Abstract

In the LHC, a large number of superconducting magnets are powered remotely by 5 superconducting links at distances of 70 up to 520 m. This innovation allowed choosing more convenient locations for installing the electrical feedboxes and their related equipment. The consolidations performed after the first commissioning campaign and the operational experience with the superconducting links over a period of several months are presented. Based on the successful application of superconducting links in the LHC, such devices can be envisaged for powering future accelerator magnets. Several possible cryogenic configurations for future superconducting links are presented with their respective figures of merit from the cryogenic and practical implementation point of view.

INTRODUCTION

Thanks to their unique performance, the use of superconducting magnets has become very common in recent particle accelerators. One of the difficulties when designing the powering and cryogenic systems is the need to supply large currents to magnets that are usually installed in areas with limited space and that may subject to intense radiation. While the superconducting magnets can be made radiation resistant and do not require regular maintenance, it is not the case for the electrical power supplies. Moreover the magnet feedboxes and their current leads need several active cryogenic components that are sensitive to radiation. There is therefore of a significant interest to locate the feedboxes and the power supplies in more convenient locations, away from radiation and in easily accessible areas. Using warm cables between the power supplies and the magnets, the distance where the power supplies can be located is limited by resistive dissipation and this does not ease the situation of the feedboxes. Powering the magnets through superconducting links, not subject to significant dissipation, allows the installation of the feedboxes and of the power supplies far away from the magnets. In the LHC five such links, based on Nb-Ti superconductors are used to remotely power magnets at distances of 70 m (4 SC links) and 517 m (1 SC link) [1].

The first part of this paper reports on the operational experience over several months of the two different types of superconducting links that are operational in the LHC. Extending from the LHC experience, possible cryogenic configurations for future SC links, in particular taking into account the possibility of using HTS or MgB₂ conductors are then presented.

OPERATIONAL EXPERIENCE WITH THE LHC SUPERCONDUCTING LINKS

In the LHC (see [1] for a detailed description), there are two types of SC links: four type-1 SC links, 76 m long, feed 3 groups of magnets and one type-2 SC link feeds the corrector circuits of one sector of the LHC. The details of the electrical circuits are given in Table 1. In all the links, the Nb-Ti superconducting cables are cooled by supercritical helium at about 3.5 bar between 4.5 K at the inlet and a maximum temperature of 6 K at the outlet.

Table 1: List of the SC links of the LHC

Type / number	Length	Current
Type-1 / 4	76 m	11 x 6kA + 12 x 600A
Type-2 / 1	517 m	44 x 600 A

Consolidations following the hardware commissioning campaign

The superconducting links were commissioned together with the LHC magnet system in 2008 [1]. The commissioning campaign showed that the 4 type-1 superconducting links were operating as planned but that the 517 m long type-2 superconducting link showed an excessive heat load that could be traced to the presence of hot spots in the two flexible sections at each end of the link. At one end of the link, the localized heat load created a temperature stratification region in the supercritical helium that resulted in premature quenching of the superconducting cable at low current. As the problem origin was the excessive displacement of bellows under the effect of external pressure, the consolidation consisted in the installation of an external self-sustained support system that avoided the displacements while providing the necessary flexibility.

The type-2 SC link was re-commissioned in 2009. The measurements show a total heat load of 17 W (corresponding to an average heat load of 0.03 W/m) which is 30 W lower than the value measured before the consolidation. This improvement corresponds approximately to the sum of the estimated localized heat loads identified during the previous commissioning campaign.

Operational experience in the LHC

The SC links of LHC have been cooled during the global cooldown of the magnet systems. All cooling operations were performed in the shadow of the cooling of the corresponding LHC sector. Typical cooling times were about 12 hours for the 76 m SC links and about 24 hours for the 517 m SC link.

The control strategy is different between the two types of SC links: for the shorter SC links, the outlet temperature of the three branches is controlled in closed loop by using the temperatures themselves as the input variables. For the longer SC link, the longer reaction time makes this control strategy more difficult and a control based on the measurement of the mass flow is used. Both regulation methods have proven very reliable, as no loss of cryogenic authorization was caused by the SC link loops during 4 months of operation. The temperature at the outlet and the mass flow for the 517 m long type-2 SC link over a period of one month are shown in Figure 1.

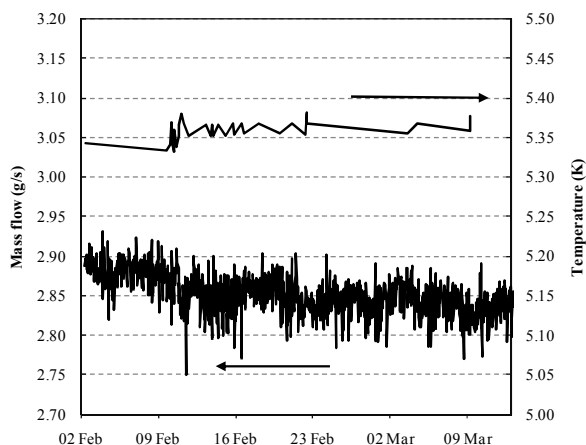


Figure 1: Mass flow and temperature over period of 1 month in 2010 for the 517 m long SC link.

The powering cycles did not have any measurable influence on the operation of the superconducting links, showing that no significant dissipation occurs in the cables or in the connections.

One of the specific characteristics of the longer SC link is the slow speed, about 25 meters per hour, of the helium in nominal operation and therefore the long time, about 20 hours, it takes for the helium to flow through the link. However, these are typical times needed to reach operating conditions in other systems of the sector, so it was not necessary to actively speed-up the re-stabilization of the SC link.

During the operation period between September 2009 and May 2010, the superconducting links and their related systems operated nominally and allowed the commissioning and operation of the corresponding magnets.

EVALUATION OF POSSIBLE CRYOGENIC SCHEMES FOR FUTURE REMOTE POWERING OF SUPERCONDUCTING MAGNETS

The operational experience at CERN and at the RHIC accelerator [2,3] has demonstrated that superconducting links are a viable solution for remotely powering superconducting magnets. In the following it is assumed that the magnets themselves are based on LTS superconductors and operate at a temperature lower than 6 K. The resistive and inductive losses due to the electrical current are assumed to be negligible with respect to the cryostat heat loads. Based on the existing experience, a safe value of 0.05 W/m can be assumed for a shielded cryostat.

Choice of the superconducting materials

In addition to NbTi, materials with higher critical temperature like MgB₂, BSCCO or 2nd generation YBCO, could be envisaged for the superconducting links [4]. However, among these new materials, only MgB₂ operating at a maximum temperature of 20 K appears to have the potential to become a realistic option [4] within a timeframe of a few years. The maximum operating temperatures, taking into account the necessary operating margins, are chosen to be 5.5 K for Nb-Ti cables and 17 K for MgB₂ cables.

General configuration

Gas cooled current leads are used to transfer to the cryogenic environment the large currents needed by superconducting magnets. Resistive leads connected to an LTS cable need a helium flow at 4.5 K of about 0.05 g/s per kA, while hybrid leads using HTS superconductors at a maximum temperature of 50 K (like the ones of LHC) [5,6] need about 0.054 g/s per kA at 20 K. At zero current these flows are about half of the nominal values. Supplying the cooling gas to the leads means that a minimum flow will be needed in the case where the cold fluids are supplied by the SC link itself. Cool-down and warm-up flows shall also be taken into account for the configuration of the links.

Experience with the LHC shows that it is highly desirable to have the possibility to split the various components of the cryogenic system by including vacuum and hydraulic barriers. As concerns the SC cables, this implies that leak tight and pressure resistant plugs must be installed at least at each end of the SC link. For the present paper we assume that the SC links are installed in their own piping and not integrated into the cryogenic fluid distribution piping and have fluid circuits controlled independently from the magnets.

Possible schemes

We evaluate two different configurations, based on the LHC but that represent also two cases likely to be encountered in future accelerators:

- A) Remote powering of a group of magnets. This configuration was envisaged for the LHC "Phase 1" upgrade [7]. Typical length of 100 m with no change in elevation, current ranging from 5 kA to 50 kA.
- B) Complete relocation of the powering of one side of an LHC sector to a surface building. Typical length of 500 m, elevation change of 100 m and total current of 150 kA.

As the magnet system operates in liquid helium, a supply of supercritical helium at about 4.5 K and 3.5 bar is assumed for this evaluation, a subcooler would probably be needed, as in the LHC, for a Nb-Ti SC link [1]. The minimum flows are shown in Table 2. For type B link, the elevation change of 100 m results in a pressure difference of more than 1 bar for supercritical helium.

Table 2: Minimum flows for the envisaged configurations

Type	Length (m)	Heat load (W)	SC link m.f. (g/s)		Leads m.f. (g/s)
			Nb-Ti	MgB ₂	
A)	100	5	0.8	0.06	0.25 – 2.5
B) Bott.	500	25	3	0.18	7.5
B) top	500	25	5.3	0.3	7.5

As expected, Table 2 shows that MgB₂ links could reduce the mass flows by a factor larger than 10 with respect to Nb-Ti cables. MgB₂ can also provide a better thermal stability and simplify the design of the current leads feedboxes [4]. However, even the heat loads and mass flows required by Nb-Ti SC links are modest compared to the typical mass flows required for accelerator magnets and their leads. The required mass flow is lower when the cold helium is supplied from the bottom; this is due to the hydrostatic pressure change and the consequent temperature change.

MgB₂ SC links

For an MgB₂ SC link the exit temperature of 17 K is ideally suited to feed HTS hybrid current leads or resistive leads. The flow needed by the leads, even for modest currents starting at 2 kA for the short links, exceeds the flow needed the SC link, making the link essentially transparent from the cryogenic point of view. A natural configuration would therefore be to use the link to supply the gas for the current feedboxes for both type A and type B links. This scheme has the advantage of returning only warm gas to the cryoplants with a resulting simple piping. One of the possible problems of operating between 4.5 K and 20 K is the large change in density of the helium over this temperature range that could result in difficulties to manage pressure-density oscillations and convective effects.

Nb-Ti SC links

For a Nb-Ti link, the cryogenic configuration depends, among other factors, on the current rating and on the choice of leads. For resistive leads that need a supply

temperature of 5.5 K, the link can naturally be used to feed the leads. If using HTS leads, however, the exit temperature of 5.5 K is not ideal and an alternate source of gas at a higher temperature should be used (potentially a factor 2 electrical power gain) while a cold return should be provided for the SC link. Cold return piping, or a parallel heater, would also be needed for links with lower currents when the gas flow needed by the leads is not sufficient to guarantee the nominal cooling of the link. A cold return scheme is probably better adapted for type B SC links where one of the ends can be located in proximity to the refrigerator. This is also a preferred scheme for forced flow cooled magnets where a cooling loop in the same temperature range is present [3].

CONCLUSIONS

Following consolidation work, the superconducting links of the LHC have been successfully operated for continuous periods exceeding one month well within the specified operational limits. The evaluation of possible future superconducting links shows that from the cryogenic point of view their usage can be envisaged without major difficulties but that an optimal operating efficiency would require a tight integration with the cryogenic system and an appropriate choice of current leads.

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