# HTS IN THE LHC & IN THE LHC UPGRADES

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**Abstract**
CERN is a major user of High Temperature Superconducting (HTS) material due to its incorporation in many of the current leads for the LHC project. There are already clear applications for HTS in the earliest upgrade scenarios, and thanks to its acquired expertise in the domain, CERN is well placed to extend the efficient use of these materials.

## 1. INTRODUCTION

CERN is an important player in the field of the application of High Temperature Superconductors (HTS). The use of HTS for the current leads in the LHC is one of the most important industrial applications of this material. By incorporating HTS material the heat conducted into the helium bath is reduced by a factor of ten, and the corresponding power consumption by a factor of three [1]. This saving was not the only benefit. By reducing the cryogenic load, it became reasonable to envisage independent powering of the quadrupole magnets in the matching sections, leading to increased flexibility in the optics of the machine. The HTS industry was also looking for a visible, commercial application of their technology, and the CERN current lead project was vitally important. It can be expected that HTS will play an increasing role in the work of consolidating and upgrading the LHC, and by virtue of its experience, CERN is well placed to take advantage of this emerging technology.

## 2. HTS FOR LHC: THE LHC CURRENT LEADS

When the possibility of incorporating HTS material in the current leads was first proposed, it was not clear exactly which technology would be most appropriate, neither was it clear how best to make use of the cryogenic system that had already been adopted for cooling the LHC [1]. The technology finally chosen was multi-filamentary Bi-2223 tape with a gold-doped silver alloy matrix. While work on prototypes had led to an improved bulk material incorporating stabilizing alloy (that is now used commercially for some applications), it was decided that, due both to its fragility and the difficulty of making very low resistance joints, the use of bulk HTS (Bi-2212, Bi-2223 or YBCO) was not appropriate for the LHC. Moreover, industry was starting to make Bi-2223 tape on a large enough scale to give confidence that their quality control would ensure reliable material and deliveries.

At the LHC, about 3 MA of current are transported via more than 3200 current leads (see Table 1). This is the largest current lead project ever undertaken. The initial intention was to apply HTS to the low current leads, but small cryogenic savings and severe geometric constraints on their integration led to a decision - following good results of tests - to adopt HTS for the higher currents.

Table 1
Type and Number of LHC current leads (excluding leads for the low-beta insertions)

| Quantity | Current rating (A) | Magnets | Type |
|---|---|---|---|
| 64 | 13000 | Main dipole and quadrupole chains | HTS |
| 258 | 6000 | Matching sections magnets | HTS |
| 708 | 600 | Corrector quadrupole, sextupole and spool pieces | HTS |
| 520 | 120 | Dipole correctors in matching sections | Resistive |
| 1504 | 60 | Dipole correctors in arcs | Resistive |

A typical Bi-2223 tape carries about 100 A in self-field at 77 K. However, at this temperature, it is very sensitive to magnetic field, and by restricting the maximum operating temperature to about 50 K one can get significantly better performance. In order to reduce the heat conductivity, a silver alloy with 5 % wt. gold replaces the customary silver matrix. This fraction of gold is found to provide the technical-economic optimum for the application.

The Bi2223 tape is extremely fragile. It was therefore decided to assemble the tapes into the more robust form of stacks of about eight tapes [2]. We initially thought we could use sintered stacks from American Superconductor (AMSC), but on analysis some samples were found to have cracks, and a CERN-developed technique of soldering was adopted as being more reliable.

The tape was specified, and over 30 km was purchased, following competitive tendering, from two suppliers (AMSC and EAS). Tape was delivered on spools in lengths of up to 300 m, inspected on reception, cut into 0.35 m pieces, and assembled and vacuum soldered (Sn-Ag eutectic) into stacks. The stacks are all characterized at 77 K (via a contract with CESI) before delivery to the lead manufacturers, where they are vacuum soldered (Sn-Pb) onto a stainless steel cylinder according to CERN procedures. The project requires about 10000 stacks. The HTS material was delivered on time and is of good quality. No material was rejected for insufficient current carrying capacity, and the stability of dimensional tolerances has been remarkable. Only a few percent of the cut lengths were deemed unacceptable due to visible bubbling. The critical current of the HTS stacks varies from 350 A (stacks from EAS tape) to about 630 A (stacks from ASC tape). All stacks were measured at 77 K in self-field, according to the 0.1 μV/cm, 1 μV/cm and 2.5 μV/cm electric field criteria. Some stacks were measured at different temperatures (from 77 K to 65 K) and in the presence of external magnetic field, parallel and perpendicular to the tape, of up to 0.5 T. Several samples of tape were irradiated using fast neutrons to verify their radiation resistance properties [3].

The tape is typically 4 mm wide and 0.2 mm thick. The filling factor is about 30 %. Each spool was electrically characterized by the manufacturer at liquid nitrogen temperature. The average critical current is about 79 A for the EAS and more than 100 A for the AMSC tape. The average n value, at 77 K and in self-field, is 25. Four short samples per each production unit underwent mechanical tests. The minimum bending radius is 50 mm, and yield strength is 100 MPa (EAS tape reinforced with Mg) and 50 MPa (AMSC tape).

The LHC current leads were conceived, designed and specified at CERN. Prototypes were built in-house, and after validation purchased according to build-to-print specifications. To save time, an initial series of each lead type was manufactured in the CERN workshops. The leads are currently being manufactured by Cecom (13 kA) and BINP (6 kA and 600 A). They are all tested in nominal operating conditions at ENEA (13 kA and 6 kA) and at the University of Southampton (600 A). Presently about two thirds of the leads are available at CERN.

Thanks to the material studies undertaken at CERN and the contacts with the companies involved, CERN has acquired considerable understanding regarding the application of HTS in its different forms, including skill in the associated calculations and the practical issues of handling and characterization. We have become acquainted with the manufacturers and users of HTS material, both for leads and for other applications. Because of this network, CERN help is now solicited by other laboratories for the design of HTS leads, not only for quasi-dc operation (as in LHC) but also for pulsed use. In addition, work is being done in parallel to characterize material, with regard to use in superconducting switches, leads and buses – and possibly in magnets too. Besides the practical work on the leads, the preparatory work for future development involves theoretical and practical studies of quench propagation, ac losses and eddy currents in HTS.

## 3. HTS AND LHC UPGRADES

### 3.1 Consolidation of the baseline LHC

Before moving to upgrades, it is likely that there will be at least two applications for HTS in the programme of Operations Support, Maintenance and Consolidation of the baseline LHC. There are magnets and bus-work in the cleaning insertions that risk being vulnerable to heating due to radiation. Suitable replacement magnets are identified, but these will benefit from purpose-designed leads and bus-work using HTS material. There is also a need for a long multi-strand HTS bus.

### 3.2 Intermediate low-beta upgrade

There may be the demand for an intermediate upgrade of the high-luminosity low-beta insertions. This is clearly the easiest way to improve luminosity should there be problems with increasing beam intensity. Moreover, due to the addition of the beam screen through the present quadrupoles, their aperture is smaller than that which was originally planned. The work presented by R. Ostojic (these proceedings) addresses this issue. The characteristics of the present leads and lead box should not constrain the optimization of the magnet system. Based on experience with the baseline LHC, ideas exist for improved types of leads and feed box that we could consider integrating into the system.

### 3.3 Injector upgrades

At the request of other laboratories, the possible use of HTS leads for pulsed use is being addressed.

### 3.4 Major low-beta upgrade

Clearly there will eventually be the need for a substantial upgrade of the low-beta insertions. Studies in progress suggest that the layout could undergo a quite radical change, including the integration of dipoles. It may well be advantageous to use HTS in at least some of these magnets. HTS material offers higher temperature margin and good radiation resistance. At the last Magnet Technology Conference, experts were optimistic about the future of HTS, forecasting regular improvement in its current-carrying capacity. This should be followed carefully and it may be interesting to develop some “react-and-wind” designs that use, or could use, HTS material. Thanks to the expertise and renown it has gained with the current lead project, CERN is well placed to follow up this line, in a complementary fashion to the upgrade magnet work being undertaken in the US LARP programme.

## 4. CONCLUSION

It is widely acknowledged that CERN is at the forefront as regards the application of HTS. For identified consolidation work on the baseline machine, as well as for an intermediate upgrade there are already potential uses of HTS. The work that is in progress on the optimization of HTS leads for pulsed operation will be directly applicable to the powering of a possible superconducting injector. CERN should also include HTS in the thinking for a major upgrade of the magnet systems for high luminosity insertions. Finally, it should be remembered that consolidation and upgrades do not only concern magnets, but also essential ancillary equipment that should be optimized together with the magnet systems. HTS is an important component of this equipment, as well as having the potential of being a conductor for future magnets.

## REFERENCES


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