Fig. 8.12. Cryogenic plant providing 18 kW @ 4.5 K. Left: compressor station. Right: cold box.

8.4 Current Leads: High Temperature Superconductors to the Fore

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Powering the superconducting magnet circuits requires the transfer of about 3 MA of current from the power converters (at room temperature) to the liquid helium environment. Good electrical conductors are also good conductors of heat, so the devices (current leads) used to transfer the current must be designed to minimize the heat in-leak yet safely carry the current. Conventional current leads achieve this by using the helium vapour that is boiled off at the foot of the lead to cool a combined conductor/heat exchanger. Such “self-cooled” leads transfer about 1 W of heat to the liquid helium bath per kA of current (compared with about 48 W/kA for a lead without vapour cooling). The interest of including a High Temperature Superconducting (HTS) section in the leads is that resistive heating in that section is absent and thermal conduction can be low, so heat in-leak is reduced [31].

Already in 1992, just six years after the discovery of High Temperature Superconductivity [32], conceptual studies were underway at CERN on using HTS in the current leads for the LHC, current leads being an evident application [Box 8.4]. Targeted tests revealed that it should be possible to make reliable HTS leads [33], and in 1999 the decision was taken to use such leads at the LHC. The aim was to obtain a saving with respect to conventional leads of a factor 10 on the required liquefaction power. Over a thousand such current leads would be needed, 64 rated at 13 kA for the main dipoles and quadrupoles, 474 rated at 6 kA for the quadrupoles of the matching sections and 520 rated at 600 A for correctors.

High temperature superconductors (HTS) **Box 8.4**

Up to 1986, practical low temperature superconductors (LTS), which first appeared in the 1960s, had been studied in depth [Boxes 4.3 and 8.1], and had been adopted for use in detector and accelerator magnets — and crucially a commodity for the magnetic resonance imaging (MRI) industry. But these materials only work at very low temperature; most magnets are cooled using liquid helium (4.2 K), which is expensive to buy and to keep cold. With this background the unforeseen discovery of ceramic materials (cuprates) that are superconducting at higher temperatures, even beyond that of abundant and cheaply available liquid nitrogen (boiling at 77 K, and a good electrical insulator), caused great excitement in the applied science community. But for accelerator scientists, the superior *high field characteristics* of these so-called "high temperature superconductors" (HTS) at *low temperatures* are far more important, as they offer the promise of magnets operating at 20 T and even higher.

The crystal structure of an HTS compound is highly anisotropic, with a stack of layers of oxides, interspersed with atoms of copper oxide The superconducting current passes preferentially in the planes between the layers rather than perpendicular to it and the intensity depends on the number of layers. HTS behaviour is not explained by BCS theory. Many types have been found, but only two developed for practical use:

BSCCO, which has two main phases, Bi-2212 and Bi-2223 (the numbers refer to atoms of Bi, Sr, Ca, Cu respectively), have critical temperatures of 85 K and 110 K. These were developed rather quickly, and are referred to as first-generation HTS. The multi-filamentary conductors are made via powder-in-tube (PIT) technology; the matrix is silver to avoid reaction with the precursor powders and let oxygen permeate during the heat treatment process. Bi-2212 can be made in the form of wires that can be cabled (before heat treatment at about 800°C, under pressure). Bi-2223 is produced in the form of tape, about 4 mm wide. The silver matrix provides good electrical stabilization. A variant using a matrix of silver-gold alloy to reduce thermal conductivity is used for HTS current leads (to limit the heat conduction into the cold environment). The cost of silver limits the likelihood of widespread large scale application.

REBCO, which has one main phase, RE-123, where RE refers to rare earth (often replaced by Y for Yttrium) and the numbers to atoms of RE, Ba, and Cu respectively, has a critical temperature (with Y) of 93 K. This second generation conductor is produced in the form of 12 mm wide tape that can be split into the "standard" 4 mm wide type. The superconducting layer is only 1 to 3 µm thick, deposited on a strong metallic substrate; a layer of copper provides electrical stabilization. At 4.5 K and 20 T current densities of 400 A/mm^2 are currently achieved. Flat cables can be assembled from shaped ribbons cut from wide tape (Roebel cables [Highlight 12.3]). This material is presently very expensive to produce, but is favoured by industry due to a potential for cost reduction.

Magnesium di-boride (MgB_2, $T_c = 39$ K) is not a true HTS, but is easier to produce in the form of multi-filamentary wire, can be cabled, and is very affordable. Although brittle and more sensitive to magnetic fields than Nb-Ti [Box 4.3], it works efficiently at 20–25 K making it well-suited for power transmission [Highlight 12.3].

The LHC HTS current lead programme was the first large-scale, mission-oriented, application of HTS materials [Box 8.4]. The work started with in-depth studies of various types of superconductor, including bulk BSCCO and YBCO materials [33], before converging on the choice of multi-filamentary BSCCO 2223 embedded in silver-gold alloy (Ag5.3wt%Au) tape. The tape was being actively developed for other projects such as power transmission, for which the BSCCO is embedded in pure silver. Silver is necessary for texturing the superconductor, but pure silver is an excellent conductor of heat. Its thermal conductivity is reduced by doping with gold. Specific methods were developed for optimizing leads combining an HTS section and a gas-cooled section. Taking advantage of the availability in the LHC of helium gas at 20 K, it was decided to operate the HTS section in the range 4.2 K to 50 K, and the gas-cooled section between 50 K and ambient temperature [31]. Prototypes were assembled and tested at CERN, where all the technological processes were developed and qualified. The design was based on the application of standard workshop practice and assembly tolerances, to enable normal engineering firms to tender. A 13 kA lead is shown in Fig. 8.13.

The procurement of the series relied on build-to-print CERN drawings and detailed assembly procedures. The 64 HTS current leads rated at 13 kA were manufactured in industry, while the large series of 6 kA and 600 A leads were made at the Budker Institute of Nuclear Physics (BINP), Novosibirsk. Close technical follow-up, with transfer of know-how acquired during the development activity, assured the quality of the production of the current leads, which was completed in a period of about two years. The required 31 km of BSCCO 2223 tape was specified and procured by CERN, where it was also soldered into stacks. These were measured in cryogenic conditions via an external contract prior to delivery to the lead manufacturers. Contracts were also placed for cold acceptance testing of all leads before integration in the LHC.

Since installation the current leads have undergone several thermal cycles and thousands of electrical cycles, as well as suffering some untoward events (e.g. stopping the flow of helium) generating the resistive transition of the HTS elements [34]. The leads were designed to withstand such events: the HTS material is shunted with sufficient normal material to carry the current during a fast ramp down (time constant 105 s in a dipole circuit) and quench protection thresholds were specifically defined to cope with the requirements of the HTS material.

In view of the success of this project, other users have moved to designing HTS leads for manufacture following standard workshop practice. For example, major aspects of the LHC design have been adopted by ITER for their current leads [35].