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Large-capacity current leads

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ABSTRACT

Feeding superconducting magnets with reliable low-loss devices is a key issue for any cryo-electrical system. Conventional or HTS current leads can be used, and cooling methods, materials, and geometries can be chosen to optimize the thermo-electrical performance of the system. The LHC magnets are powered via more than 3000 current leads transporting altogether about 3 MA of current. With thousands of leads, the LHC lead project represents today the largest project of its kind ever undertaken. Following a review of the LHC lead project, an overview of the choices that can be made for the optimization of large capacity current leads is presented. Examples are given of other leads for large scale magnet systems for which the use of HTS is being envisaged.

1. Introduction

The powering of a superconducting system relies on warm and cold electrical components. Power converters, protection elements, as well as normal and superconducting buses, are chosen to match the static and dynamic characteristics of the system and, in the case of large scale magnet systems such as those of particle accelerators, to take into account the integrated nature of the machine. The current leads that provide the electrical link between room temperature and the cryogenic environment also link the environments thermally, and are a crucial element that can have a significant impact on the system performance.

The design of a current lead is intimately coupled with the system that it serves. Electrical, cryogenic, geometrical, and environmental requirements are the key parameters that influence the choices for its optimum design. The main goal consists of minimizing the heat load into the cryogenic environment: this applies both to large systems, operating at liquid helium temperature, and small isolated systems, e.g. cryo-cooled devices, and the derived savings serve to free capacity for other use. However, the additional investment required to make this possible must be subjected to a stringent cost/benefit analysis.

Optimized conventional DC current leads operating between room temperature and the liquid helium environment conduct into the cryogenic bath about 47 W/kA, when they are conduction-cooled, and 1.1 W/kA, when they are self-cooled using the enthalpy of the helium boil-off [1]. These performances, which do not depend on the material properties and are due to the Wiedemann–Franz law, can be improved by replacing the bottom part of the conventional lead with High Temperature Superconducting (HTS) material, characterized by low thermal conductivity and zero electrical resistivity. In this way, a reduction of heat load into the cryogenic bath of a factor of about 10 can be readily achieved [2]. The correspondent saving in total exergetic cost of the refrigeration depends on the cooling, i.e. type and temperature of the available cryogen, and on the design of the resistive upper part of the lead, but is typically a factor of three less than for a lead that does not incorporate an HTS section [3]. The precise system requirements play an essential role in the choice between conventional and HTS leads.

In this paper, the LHC current lead project is presented, from the conceptual design up to the series production of more than a thousand units and their integration in the LHC machine. Examples are given of other large scale systems envisaging the use of HTS leads for the powering of superconducting magnets.

2. LHC current leads

The powering of the LHC machine requires the transfer of about 3 MA of current to feed more than 1800 superconducting circuits operating at liquid helium temperature. Apart from the low current leads, powering the dipole corrector magnets and operating at currents ranging from 60 A to 120 A, all the other leads incorporate High Temperature Superconducting material. There are thus 1182 HTS leads operating at currents ranging from 600 A to 13,000 A (see Table 1). They are located in the LHC tunnel, where they are grouped right and left of each of the eight LHC beam crossing points, to feed the superconducting circuits located in each of

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the corresponding eight sectors. The power converters are located in underground caverns, parallel to the LHC tunnel, and room temperature power cables provide the electrical connection to the warm end of the leads.

Conventional self-cooled current leads have a minimum heat load into the helium bath of about 1.1 W/kA [1]. This value, which is practically independent of the material properties, represents the optimum performance of a lead operating at nominal current. The correspondent geometry depends on the properties of the conductor and is characterized by an optimum shape factor (SF), given by the product of the current (I) times the length of the conductor (L) divided by its cross-section (A_{Cu}). This optimization is based on a number of assumptions: equal temperatures of helium and conductor at the cold end of the lead, perfect heat exchange between the conductor and the gas, and the validity of the Wiedemann–Franz law that establishes a direct proportionality between the product of thermal conductivity and electrical resistivity and the temperature. Furthermore, the helium mass flow is bound to the heat load by its latent heat of vaporization. These assumptions make it possible to use analytical models to calculate the optimum performance of a self-cooled lead. This method cannot, however, be called upon to optimize leads that are cooled by flow of helium at intermediate inlet temperature, and that are not determined by vapor boil off due to heat input from the lead.

The LHC HTS current leads incorporate HTS material in the form of stacks of Bi-2223 tape. The design of these leads is such that, by cooling their upper, resistive part with 20 K helium gas, available at that temperature from the recovery line cooling the accelerator beam screen, the temperature of the warm end of the HTS is maintained at 50 K [3]. These operating conditions are favorable for the HTS electrical performance, and represent an optimum in terms of exergetic cost of the refrigeration within the temperature levels of the LHC cryogenic system. Other systems, having available either helium gas at different temperatures or different cryogens, must be optimized taking into account their particular boundary conditions.

The silver gold matrix of the tape serves as a protective shunt through which current can pass without excessive heating during the discharge of energy from the magnet system in case of quench of the HTS (e.g. due to cooling failure). The longest time constant for this discharge is associated with the main dipole circuit, and is 120 s.

The conceptual and detailed design of the LHC leads was made at CERN, where pre-series units were also assembled and tested [4]. The extensive R&D program was followed by closely controlled construction and tests in cryogenic conditions of all the leads, in order to give confidence in the long-term application of these devices on such a large scale.

2.1. Normal conducting section

The cooling of the resistive part of the HTS lead can be made with cryogens at any temperature below the critical temperature of the HTS [5]. In the case of helium, the whole range 5–85 K can be exploited and, for a given inlet temperature of the gas, a wide range of operating temperatures for the warm end of the HTS (T_{HTS}) can be established. The impact of these parameters on the lead performance is described by a system of one-dimensional differential equations expressing the heat balance between the conductor and the coolant. Boundary conditions are the temperature at the cold end of the heat exchanger and the inlet temperature of the gas (T_{He}). The minimum helium mass flow and the corresponding lead geometry (SF), together with the conductor (T_{Cu}) and helium temperature profiles, can thus be determined. The results are shown in Figs. 1 and 2, where the curves represent respectively the calculated minimum flow rate and the corresponding lead shape factor for T_{He} varying from 5 K to 80 K and T_{HTS} from 20 K to 85 K. These curves map the performance of helium gas cooled resistive heat exchangers made of copper having a residual resistance ratio (RRR) of 70, and optimized with different boundary conditions. The curves in Fig. 1 depend on the material properties, but are generally valid to within 10–20%. For instance, the use of copper with RRR = 150 requires an increase of the flow rate by about 20% when $T_{HTS} < 50$ K and by about 10% in the other cases. The impact on the SF is, however, more important, requiring an increase of 60% in the first case. For copper with a different RRR, the difference in thermal and electrical properties becomes significant at temperatures below 50 K, which explains the more marked variation in parameters at temperatures below this value. Fig. 3 shows the calculated temperature profiles of the heat exchangers of Fig. 1 for the case $T_{He} = 20$ K and T_{HTS} in the range 30–80 K. In a similar way as for conventional self-cooled current leads, the optimum performance in the resistive part of the HTS leads is characterized by the zero slope of the temperature profile of the conductor at the warm end.

The LHC current leads were optimized for operating at nominal current with $T_{HTS} = 50$ K and $T_{He} = 20$ K. The measured mass flow rates are 0.6 g/s for the 13,000 A leads and 0.03 g/s for the 600 A leads, in good agreement with the 0.045 g/s kA shown in Fig. 1. The 6000 A LHC HTS leads require a flow of 0.33 g/s, intentionally slightly higher than the ideal flow rate in view of the requirement to be able to run these leads in DC mode with currents of up to 7500 A. In order to limit overcooling in standby mode with no current, T_{HTS} is adjusted to 70 K. In stand-by, heating must nevertheless be applied to the warm end of the lead to avoid condensation, and to this end a secondary heat exchanger, heated electrically, is installed in the terminal to ensure that the gas is recovered at room temperature. In the case of the 13,000 A lead the heating power is 360 W.

Table 1
Lead count for the LHC machine. The 60 A and 120 A leads are resistive

Number of leads	Current rating (A)	Magnet type
64	13,000	Main dipoles and quadrupoles
298	6000	Insertion dipoles/quadrupoles
820	600	Corrector magnets
2104	60–120	Corrector magnets

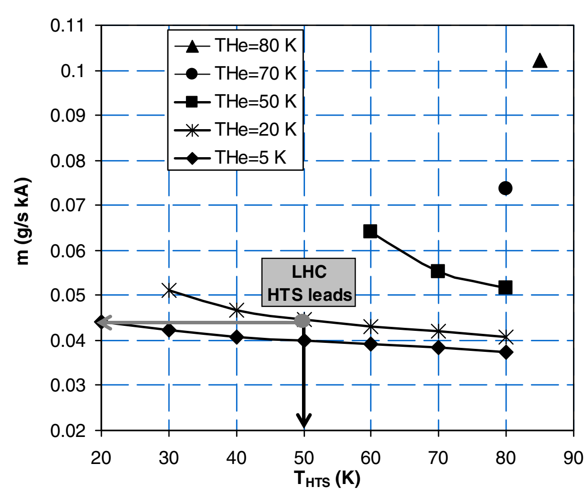

Fig. 1. Helium mass flow rate for the resistive part of the lead as a function of the temperature at the cold end of the heat exchanger.

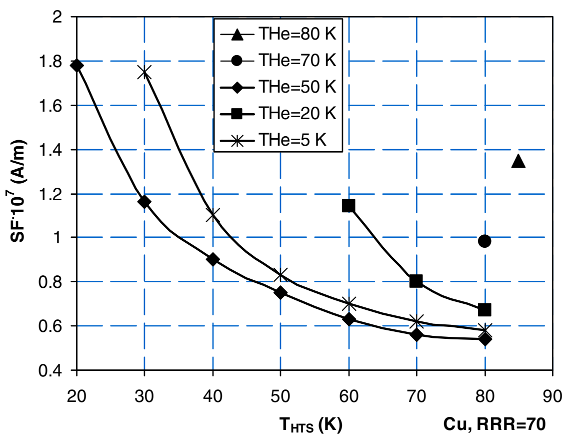

Fig. 2. Shape factor as a function of inlet temperature of the coolant gas.

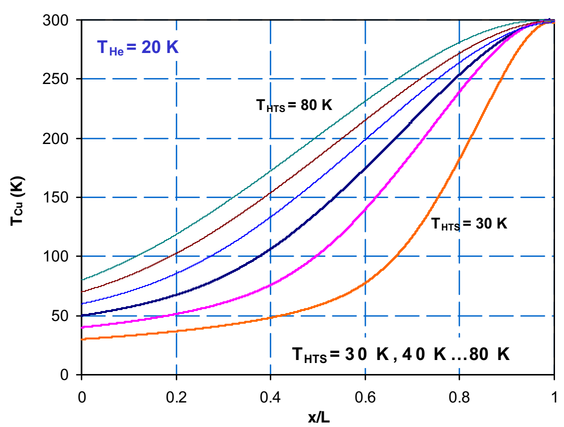

Fig. 3. Temperature profile of resistive heat exchanger (Cu with RRR = 70) for T_{He} = 20 K and T_{HTS} = 30 K, 40 K, 50 K, 60 K, 70 K and 80 K (from bottom to top).

The warm end of the HTS can be cooled using liquid nitrogen. In this case the optimization process for the heat exchanger is the same as for conventional self-cooled leads. The minimum heat load at 77 K is about 23 W/kA.

2.2. HTS section

The HTS part of the LHC current leads is made of stacks of Bi-2223 tapes with a gold-doped silver matrix, where the gold percentage is about 5 wt% [6]: the doping is to ensure a low thermal conductivity. It is convenient to use tape stacks in large capacity leads on account of their robustness. The stacks have a constant cross section. Though theoretically better, tapered stacks are more fragile, add electrical resistances, and the small gain in thermal performance is offset by the additional complication of the manufacture. The critical current (I_c) of a stack depends on the number (n) and characteristics of tapes, and shows a typical reduction (for a stack of about eight tapes) of 30% with respect to the value calculated by multiplying n times the Ic of each tape. This is in agreement with predictions from a finite-element model of a stack [6]. The final geometrical disposition of the stacks in the HTS section – flat on the perimeter of a support tube – is such as to minimize the perpendicular component of the magnetic field.

The HTS operates in a range of temperature from 4.2 K to T_{HTS}, either in self-cooled, as for the LHC leads, or in conduction-cooled conditions. Convection cooling due to gas boil-off can improve the thermal performance by a factor of up to 5 with respect to the purely conduction-cooled option.

The total heat load into the helium bath depends on T_{HTS}, on the number of tapes needed for transporting the current and on the requirements of the electrical circuit with regard to the protection of the HTS part. A reduction by a factor of 10 in heat load with respect to conventional self-cooled leads has been calculated and measured on the 13,000 A LHC HTS leads [3]. The total reduction in overall cooling power is a factor of 3.

2.2.1. Tapes

The Bi-2223 multi-filamentary tape was supplied to CERN on spools in lengths of 100–300 m [6]. The two suppliers, AMSC and EHTS, performed critical current measurements on each spool of tape. Measurements of mechanical characteristics (Young's modulus, tensile strength at room temperature, permitted bending radius, etc.), and filling factor, were made on four short samples extracted from each unit length, the unit length being defined as the length of tape obtained from the same billet and that underwent, during production, the same mechanical and thermal processes. The tapes from the two suppliers have the same cross section (4 mm wide, 0.2 mm thick) but different characteristics. The average critical currents measured on each spool (1 μV/cm criterion, 77 K, self-field) are given in Fig. 4. The minimum, maximum, and average critical currents were 103, 147 and 120 A for AMSC tape and 70, 87 and 79 A for EHTS tape; standard deviations were 7 A and 4 A, respectively. The average n-value of the superconductor measured in self-field at 77 K was 20 for the AMSC material and 30 for the EHTS material.

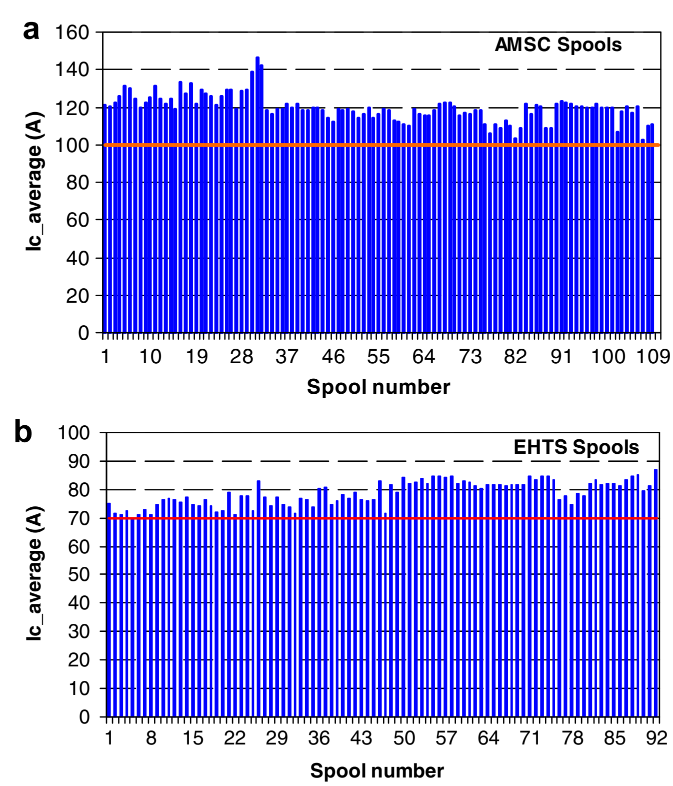

Fig. 4. Average critical current measured on different spools of tape used for the leads (AMSC, Fig 4a, and EHTS, Fig. 4b).

2.2.2. Stacks

Stacks of 0.35 m in length were made by soldering together tapes using 96.5Sn–3.5Ag eutectic alloy. No flux was used to avoid the delicate post-soldering cleaning operation and potential corrosion due to flux residues. The cut tapes were cleaned and assembled in graphite moulds with interleaved solder foil. Soldering was done in a horizontal vacuum furnace with a peak temperature of 240 °C for 15 min. Three types of stack were made: (1) with 8 AMSC tapes (AMSC-8), (2) with 7 EHTS tapes (EHTS-7), and (3) with 9 EHTS tapes (EHTS-9). The stacks were assigned to leads according to their current ratings.

The critical current of all of the HTS stacks was measured in a saturated liquid nitrogen bath and in self-field conditions. Tooling was designed by CERN to allow the measurement of up to twenty stacks in series. The electrical connections between stacks and to the power terminals were made by clamping gold-plated copper blocks to the HTS stacks with a controlled torque. The voltage taps used for deriving the critical current were provided by spring loaded needles, pressed against the HTS conductors.

For each stack the critical currents corresponding to electric fields (E) of 0.1, 1 and 2.5 μV/cm were derived [6], as well as the *n*-value, calculated as the slope of the logarithmic plot of the voltage versus current in the range from 0.1 to 2.5 μV/cm. The resistance of the contact to the stacks was always $\leqslant 1.5\ \mu\Omega$ at 77 K.

All the 10,800 stacks required for producing the leads were made at CERN and tested at CESI in Italy before being issued to the lead manufacturers. During transport and storage, Bi-2223 tapes and stacks were enclosed in protection boxes, and sealed in nitrogen gas or vacuum to protect the surface against oxidation.

2.3. Manufacture and test

The leads were designed as build-to-print components. Prototypes were first manufactured at CERN [4], and after validation through extensive testing contracts were made with industry and external laboratories for the series production. All leads were fully tested in independent laboratories under separate contracts [7,8].

2.3.1. Assembly

The assembly of the lead involves a sequence of vacuum brazing, vacuum soldering, electron-beam welding and TIG welding procedures, the good quality of which is essential for the success of the lead design [4]. The lead consists of three main sub-assemblies: a copper terminal block, a fin-type heat exchanger within an insulating vacuum enclosure, and a superconducting section, as illustrated in Fig. 5. The terminal block is made of OFE copper, with brazed stainless steel inserts; it also contains a small heat exchanger made up from thin perforated copper plates brazed into a central cavity.

The main heat exchanger/lead is made of copper of controlled RRR and is of the fin type. Small segments are removed from the edge of the fins in an alternating fashion, to ensure that the coolant gas snakes up the heat exchanger to establish a regular temperature gradient. The superconducting section consists of a rigid support with the HTS stacks and LTS (low temperature superconducting) wires that connect to the magnet bus. The support is a grooved stainless steel tube with brazed copper terminal blocks at each end. The LTS wires are soldered into recesses under the grooves at the cold end of the section, and the HTS stacks are soldered into the (copper flash plated) grooves over the entire 300 mm length. Finally the three major components are connected by electron beam welding. Before embarking on the production, it was necessary to ensure detailed validation of each of the required procedures.

2.3.2. Test

At appropriate times during fabrication the leads were subjected to voltage and leak test, and as a final test every lead was tested up to maximum current. No leads failed at the stage of the final test. A few leads were however damaged during handling and transport, and had to be replaced.

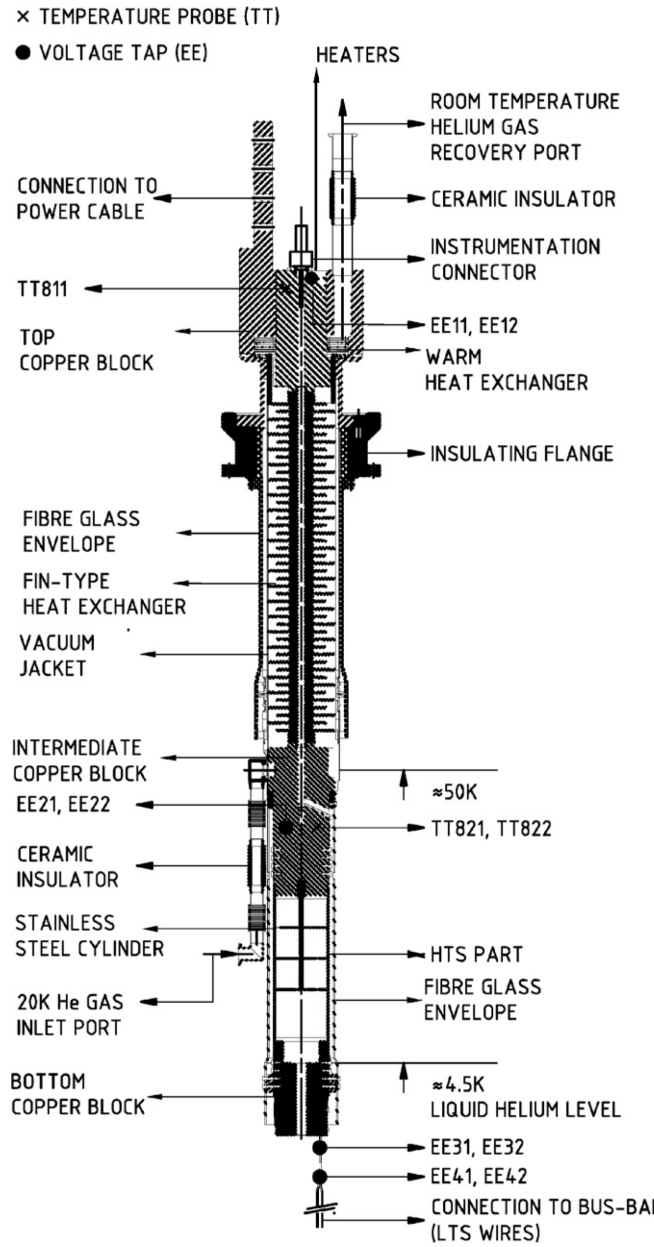

Fig. 5. Schematic drawing of a 13,000 A lead for the LHC.

2.4. Installation and commissioning

All the leads have now been manufactured, tested and installed into their cryostats, to constitute the distribution feedboxes (DFBs) that enable power to be delivered to the superconducting magnet systems of the LHC (see Fig. 6) [9]. The commissioning has started, and will continue in 2008. Up to now there have been no problems with the current leads [10].

3. Other large capacity current leads

Besides the LHC, other accelerators envisage the use of large capacity HTS current leads. Among them, the ITER and the GSI/FAIR

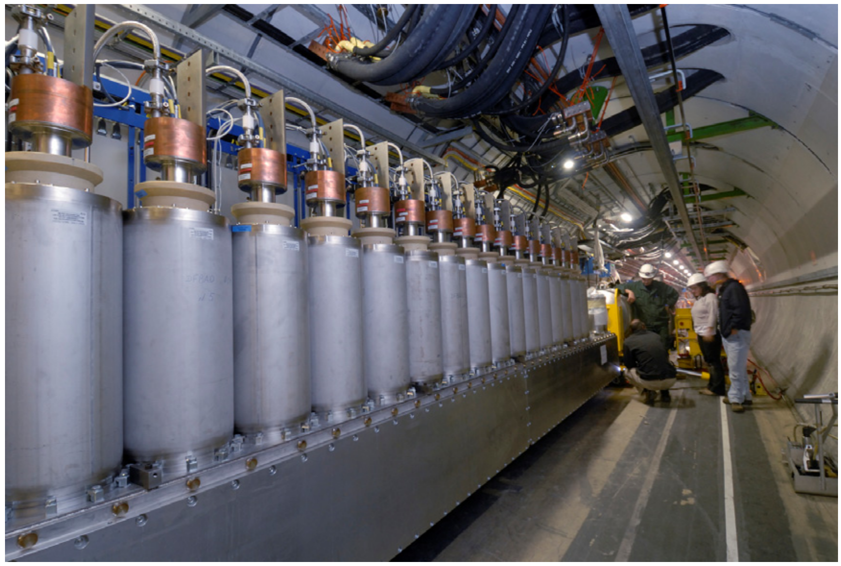

Fig. 6. Leads installed in a cryostat in the LHC tunnel.

project will require leads operating in both DC and pulsed mode [11,12].

3.1. HTS leads operating in DC mode

The ITER PF coils will require 18 leads rated at 68 kA. The ITER cryogenic system has helium gas available at about 50 K, and the optimum performance of the resistive part of the leads cooled with this gas can be derived from Fig. 1. The HTS element can be made to operate at a temperature between about 60 K and 80 K.

3.2. HTS leads operating in pulse mode

3.2.1. Normal conducting section

HTS leads dimensioned for operating in DC mode at the maximum current can be used to power pulsed superconducting magnets. However, if the superconducting circuit never operates in DC conditions, the leads will be constantly over-cooled, and it will always be necessary to apply heat at their warm end for maintaining the room temperature. Otherwise, humidity and ice will build up, compromising the electrical insulation of the circuit.

The analysis of leads operating in AC mode was made by solving numerically the system of non-linear second order partial differential equations expressing the heat balance between the lead and the gas in transient conditions [5]. An appropriate algorithm for solving this system of equations is the method of lines, a semi-discrete method that uses finite differences for the spatial (x) derivatives and ordinary differential equations for the time (t) derivatives. As for the DC case, material and helium gas properties are temperature dependent. Boundary conditions are the temperatures T_{He} ($T(x=0,t)$) and T_{HTS} ($T(x=0,t)$). Initial conditions are temperature profiles of helium ($T(x,t=0)$) and conductor ($T(x,t=0)$). Several cases have been studied. For illustration we consider here the case of $T_{He} = 20$ K and $T_{HTS} = 50$ K.

3.2.1.1. Slow-cycle. The ITER PF coils. The ramp rate of the six ITER poloidal coils (period of 1800 s) was taken from an ITER reference operation scenario (Fig. 7) [5].

A copper heat exchanger with RRR = 70 and optimized for operating in DC mode ($A_{Cu} = A_{DC}$) at the maximum current ($I_{MAX} = 45400$ A) requires a flow of 2.2 g/s. The same heat exchanger carries the current $I(t)$ of Fig. 7 with a flow of 1.6 g/s.

If the conductor cross-section is increased by 20% in the top half of the upper part ($L = 0.5$ m), the lead operates in the same temperature range with a flow of 1 g/s. No overheating above room temperature occurs, thanks to the increased cross section in the warmer region, and the peak voltage is 75 mV when the current is $|I_{MAX}|$. The highest temperatures of each cycle occur in the time interval 590–700 s, when the current increases up to I_{MAX} with the highest ramp rate of 113 A/s. The calculated voltage drop (U) is shown in Fig. 8, and temperature profiles are shown in Fig. 9.

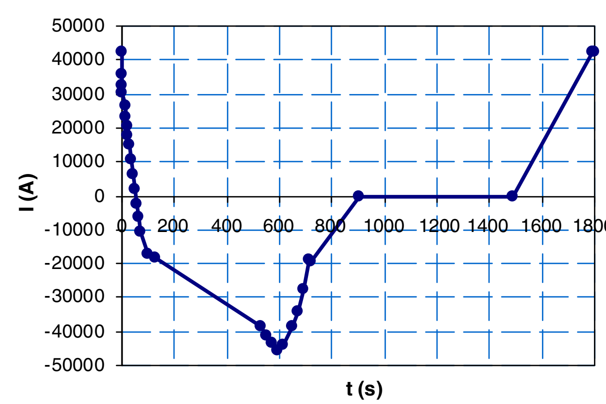

Fig. 7. Reference cycle of the ITER poloidal coils ($t = 1800$ s, $I_{max} = 45.4$ kA).

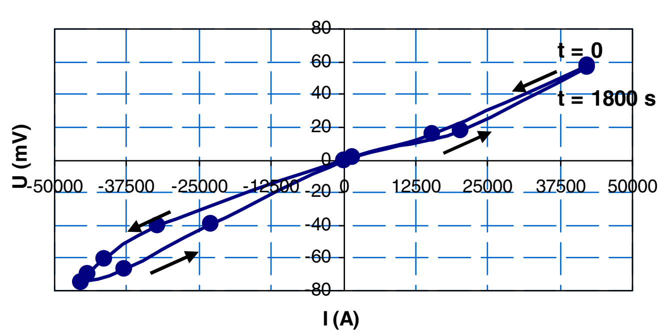

Fig. 8. Variation in voltage drop though the cycle of Fig. 7.

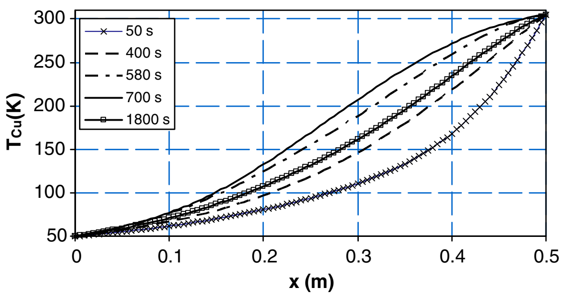

Fig. 9. Temperature profile for the lead with stepped profile at time = 50 s, 400 s, 1800 s, 580 s, 700 s from bottom to top and with current of Fig. 7.

3.2.1.2. Fast-cycle. Dipoles for the SPS upgrade and for the FAIR project.

The need for fast pulsed superconducting magnets (1 T/s) for the SPS injector is being studied in the framework of future LHC upgrades: pulse repetition rates of 12 s bring the current from injection (500 A) to 10,000 A (Fig. 4) [13].

Fast ramp rates will be used for powering of the superconducting dipoles (4 T/s) of the GSI FAIR project, where pulsed triangular cycles of frequency 1 Hz and I_{MAX} = 6000 A have been used for the simulations [12].

For the SPS leads, the use of a variable cross section, with a 30% reduction of the A_{Cu} value in the lower half part, enables a reduction of the flow from 0.3 g/s to 0.25 g/s. After about 20 min of run, the temperature profile reaches a practically zero slope at room temperature with temperature variations of less than 1.5 K during a cycle.

In the case of the GSI/FAIR leads, the increase of the cross-section in the top half gives a reduction in the nominal flow rate to 0.14 g/s. The maximum voltage during a cycle is 89 mV after 0.5 s, and the temperature variations within one cycle are less than 1 K.

3.2.2. HTS section

The AC losses of the superconductor have to be added to the thermal conduction losses. Hysteresis losses in the superconductor can be calculated by simplifying the superconducting geometry of the Bi-2223 tapes in the stack with a single core ellipse and by applying the Norris formula [14]. This assumption is in good agreement with losses measured on LHC stacks [15]. In the leads, the HTS operates at fixed frequency and fixed transport current, and the normalized current (I_{MAX}/I_c) decreases from T_{HTS} down to the cold end of the superconductor (I_{MAX}/I_c ($T(x)$). The advantage of operating along the stack's length at currents well below the critical one – together with the very low frequencies of the cases of interest and the relatively short length of the superconductor (L is usually about 0.5 m) – reduces the hysteresis losses to a small fraction of the thermal conduction value. For instance, the hysteresis loss of an HTS element for the previously-cited GSI lead (L = 0.4 m), operating at I_{MAX} = 6000 A with T_{HTS} = 77 K and a current equal to 90% of its critical value at that temperature, is about 12 mW.

For the eddy current losses in the silver–gold matrix, the dependence of the resistivity on the temperature – it decreases by a factor of about 2.5 from 77 K down to 4.2 K – would mean they have some impact at higher frequencies (about 100 mW for the GSI HTS module operating at 50 Hz). At the low frequencies of interest for this study, they represent a negligible fraction of the total losses.

4. Conclusion

HTS leads offer the potential of a considerable saving power in the cryogenic system. The incorporation of more than thousand units of HTS leads in the LHC machine has offered a unique opportunity for a real mission-oriented large scale application of HTS material. Experience from the cryogenic test of series units and LHC operation is positive, and provides the basis for increased confidence in this type of equipment.

The operating conditions of an HTS lead must be chosen strictly regarding the framework of the cryogenic and electrical system within which the lead is supposed to operate. The operating conditions have an impact on the design choices, the optimization process and thereby on the global exergetic cost of the refrigeration.

Based on the design process adopted for the LHC HTS leads, the principles of optimization of both DC and pulsed HTS current leads have been presented. Guidelines have been given for optimizing performance with different boundary conditions in DC mode, and it has been shown that for pulsed operation a variable cross-section in the resistive part brings certain advantages. The incorporation of a resistive heat exchanger with non-uniform cross-section should not over-complicate the manufacturing of leads for pulsed operation. It is, however, important to address the full range of possible excitation cycles in establishing the final dimensions of leads designed for pulsed use.

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