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1.9 K Test Facility for the Reception of the Superconducting Cables for the LHC

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***Abstract* - A new test facility (called FRESCA) is under construction at CERN to measure the electrical properties of the LHC superconducting cables. Its main features compared to existing test facilities are: a) independently cooled background magnet, b) test currents up to 32 kA, c) temperature between 1.8 and 4.5 K, d) long measurement length of 60 cm, e) field perpendicular or parallel to the cable face, f) measurement of the current distribution between the strands. The facility consists of an outer cryostat containing a superconducting NbTi dipole magnet with a bore of 56 mm and a maximum operating field of 9.5 T. The current through the magnet is supplied by an external 16 kA power supply and fed into the cryostat using self-cooled leads. The lower bath of the cryostat, separated by means of a so called lambda-plate from the upper bath, can be cooled down to 1.9 K using a subcooled superfluid refrigeration system. Within the outer cryostat, an inner cryostat is installed, containing the superconducting cable samples. This approach makes it possible to change samples while keeping the background magnet cold, and thus decreasing the helium consumption and cool-down time of the samples. The cable samples are connected through self-cooled leads to an external 32 kA power supply. The lower bath of the inner cryostat, containing the sample holder, is separated by means of a so called lambda-plate from the upper bath and can be cooled down to 1.9 K. The samples can be rotated while remaining at liquid helium temperature, enabling measurements with the background field perpendicular or parallel to the broad face of the cable. Several arrays of Hall probes are installed next to the samples in order to estimate possible current imbalances between the strands of the cables.**

I. Introduction

In the years 1999-2004 about 6400 km of superconducting NbTi cable will be manufactured in industry for the production of the coils for the main magnets of the Large Hadron Collider at CERN [1]. The main dipoles use “Cable 1” for the inner layer and “Cable 2” for the outer layer, while the main quadrupoles use only “Cable 2”. The principal characteristics of these cables are given in Table I.

Part of the quality acceptance tests of these cables is the measurement of their critical current, or I_C-measurement.

The electrical characteristics of a NbTi superconductor can often be well described by the so called ‘*n*-power relation’ $U=U_0(I/I_C)^n$ valid in the first part of the resistive transition. The critical current I_C and the *n*-value will be defined at a resistivity ρ_C of 10^{-14} Ωm over the entire cross-section of the conductor, so that: $U_0/l=I_C\rho_C/A$ with l the length of the cable over which the voltage is measured and A the cross-section of the cable. For the LHC cables U_0/l is typically ca. 5 µV/m.

The cables will be delivered in unit lengths of about 500-800 m. It is estimated that an I_C-measurement will be performed on about one out of four unit lengths, giving a total of more than 3000 measurements, with a peak of about four measurements per day. The major part of these measurements will be performed at BNL mainly at 4.3 K, using similar test stations as the one used for the reception tests of the RHIC and HERA cables [2],[3].

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TABLE I.
MAIN CHARACTERISTICS OF CABLE 1 AND CABLE 2

	Cable 1	Cable 2
Width	15.1 mm	15.1 mm
Mid-thickness at 50 MPa	1.900 mm	1.480 mm
Keystone angle	1.25 degrees	0.90 degrees
Cable pitch	115 mm	100 mm
Nr of strands	28	36
Min. I_C at 1.9 K	13750 A @ 10 T	12960 A @ 9 T

In this paper the design of the CERN cable test facility (called FRESCA) is described, which will especially be used for I_C-measurements at 1.9 K. It is estimated that about one out of ca. 12 unit lengths will be measured in FRESCA, giving a total of about 1000 tests over a 5 year period, with a maximum of two samples per day. Besides the I_C-measurement, several implemented features make it possible to perform additional research on Rutherford-type cables.

In section II the general design of the test facility is presented followed by a more detailed description of the main components. In section III the measurement instrumention is discussed.

II. Design of FRESCA

A. General Lay-out

An already manufactured LHC 1.3 m long dipole model magnet (with an aperture of 56 mm) is used as the background magnet, having:

a) a sufficiently large field (up to 9.5 T at 1.9 K) in order to determine I_C around the operating field of LHC (8.34 T),
b) a field uniform over a sufficiently long length (ca. 600 mm) to measure the *UI* curve over ca. 5 times the cable pitch (ca. 100-115 mm – see Table I). This is important to obtain a cable I_C which is a good average of all the strands in the cable, and less sensitive to non-uniform soldering resistances between the sample and the current leads [4].

Due to the long cool-down time of the magnet (weighting almost 2000 kg) a “double cryostat concept” is chosen (see Fig. 1). The magnet is put in a separate cryostat (called Outer Cryostat - see section II-B), which is cooled down independently. The magnet is connected through a pair of 18 kA current leads to a 16 kA current supply (section II-E). The samples to be tested are housed in a second cryostat (called Inner Cryostat – see section II-C) penetrating through the aperture of the magnet. In this way the magnet can be kept cold while each day a new sample is cooled-down, measured, and warmed-up. Besides the advantages of a significant reduction of the helium consumption and time, the "double cryostat concept" makes it also possible to determine I_C over the entire range 1.8-4.3 K up to fields of 9.5 T (by keeping the magnet at 1.9 K). Furthermore, the magnet will not undergo many thermal cycles, which could otherwise maybe negatively affect its stability. A disadvan-tage however of this concept is that only a very limited free aperture of 53 mm diameter is available for housing the inner cryostat with the sample holder. Therefore, a 1.5 m long dipole magnet having a 88 mm bore is presently under construction, which will later replace the existing dipole.

Both the inner and outer cryostats are vertical double-bath cryostats operating with HeII in the lower bath (or 1.9 K part) and HeI in the upper bath (or 4.3 K part), both at atmospheric pressure. The 1.9 K parts are cooled down by means of two subcooled superfluid refrigeration systems

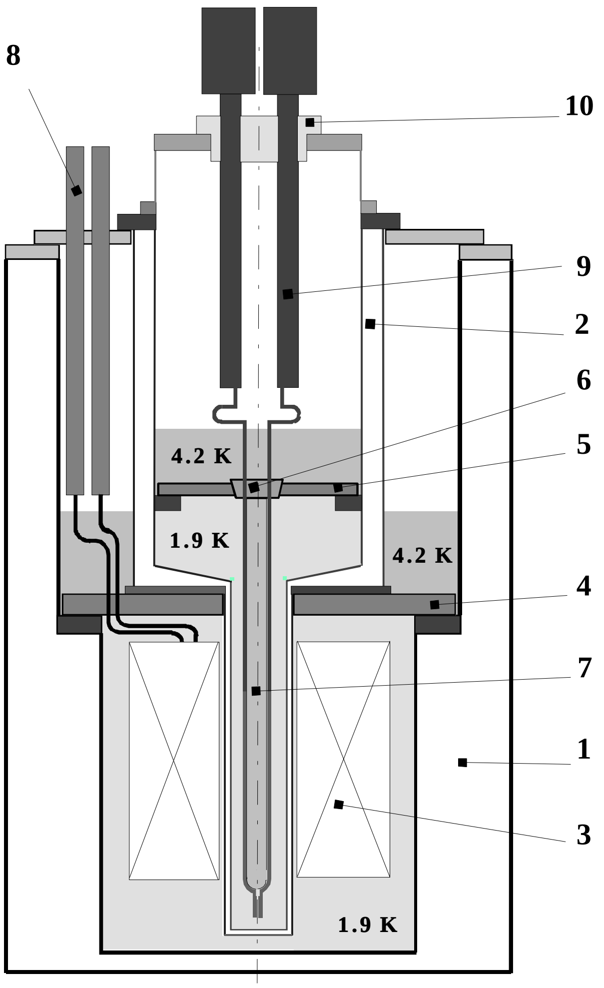

Fig. 1. Schematic lay-out of FRESCA. 1) Outer cryostat, 2) Inner cryostat, 3) Magnet, 4) λ-plate outer cryostat, 5) λ-plate inner cryostat, 6) λ-plate sample holder, 7) Sample holder, 8) Current leads magnet 18 kA, 9) Current leads sample 32 kA, 10) Rotating system for the sample holder.

(section II-E). Two λ-plates (sections II-B/C) thermally separate the 1.9 K parts from the 4.3 K parts.

Through the centre (with a diameter of 300 mm) of the inner cryostat the sample insert can be installed. The sample insert consists of the sample holder (section II-D), one pair of 32 kA self-cooled current leads (section II-F) and a 300 mm diameter λ-plate, fitting tightly into the λ-plate of the inner cryostat. The 32 kA current leads are connected to a 32 kA current supply (section II-F) via a so called "quick-disconnect". This system enables a fast connection between the top of the 32 kA current leads and 2x8 4 kA water cooled leads by means of pressurised air. The system moves away in order to have free access to enter and remove the sample insert through the centre of the inner cryostat.

A special feature of FRESCA is the possibility to rotate the sample insert while keeping the inner cryostat and the sample holder cold and filled with helium. Rotation over 90 degrees causes the maximum field (i.e. the sum of the applied field and the self-field) to move from the edges to the broad face of the cable. I_C-measurements in both directions can hence reveal a possible I_C-degradation in the strongly deformed edges of the cable.

B. *Outer Cryostat*

The outer cryostat consists of a stainless steel inner and outer vessel, with an outside diameter of 1.6 m and a height of 3.64 m. Both vessels are connected by a top flange which contains a vacuum pump inlet, two safety relief valves (1.5 bar abs) and two rupture disks (2 bar abs).

The thermal insulation inside the vacuum space between the two vessels consists of two polished copper radiation shields, one at ca. 100 K and one at 4.3 K and multi-layer reflective super-insulation. About 30 layers cover the 100 K screen and the upper part of the inner vessel and about 10 layers cover the 4.3 K screen. Over a height of 700 mm, five reflective radiation screens are mounted below the top plate.

The inner vessel has a support flange at medium level, on which the stainless steel λ-plate is placed. A tight contact between the flange and the λ-plate is assured by a 1 mm thick teflon seal. The full mass of the magnet (ca. 2000 kg) has to be taken by the λ-plate and therefore by the support flange. The λ-plate has a diameter of 1334 mm and a thickness of 60 mm. On top of the λ-plate a G10-plate is fixed for better thermal insulation between the two baths.

The λ-plate contains feed-throughs for two over-pressure valves, two magnet current leads, the helium transfer line, and two connectors for electrical wires.

C. *Inner Cryostat*

The inner cryostat consists of a stainless steel inner and outer vessel, connected by a top flange which contains a vacuum pump inlet, one safety relief valve (1.5 bar abs) and one rupture disk (2 bar abs). In the lower part the inner and outer dimensions of the cryostat are only 45 resp. 52 mm.

The thermal insulation inside the vacuum space between the two vessels consists of multi-layer reflective super-insulation. About 20 layers cover the upper part of the inner vessel and 3 layers cover the lower part. Over a height of 400 mm, three reflective radiation screens are mounted below the top plate.

The inner vessel has a support flange at medium level, on which the stainless steel λ-plate is placed. The contact between the flange and the λ-plate is sealed by either a 1 mm thick teflon joint or by a thin layer of vacuum grease. The λ-plate has an outer diameter of 760 mm and a thickness of 60 mm. On top of the λ-plate a G10-plate is fixed for better thermal insulation between the two baths. The λ-plate contains feed-throughs for the helium transfer line, two over-pressure valves, and two connectors for electrical wires.

D. Sample Holder

The bifilary shaped sample consists of two cable pieces of about 2 m each (samples 1 and 2). The keystoned samples of 15.1 mm width are put in series and connected to the current leads by clamped connectors and soldered together at the bottom. The series connection of the two samples implies that the electric properties of both cables can only be determined if the critical currents of the two samples match to within 3-4%. This criterion is very likely to be fulfilled during the mass production of the cables for LHC, so that it will be almost always possible to measure two samples of the same supplier per cool-down.

The two cable pieces are pressed in-between two stainless steel bars to about 60 MPa (see Fig. 2) to avoid strand/cable movement due to electromagnetic forces which could lead to premature quenching. A 2 m long U-shaped G10 piece electrically insulates the samples from the sample holder and makes it possible to test cables with different dimensions with the same sample holder. Small holes in the G10 piece provide helium access for the sample. In-between the cables a kapton foil insulates both samples from each other.

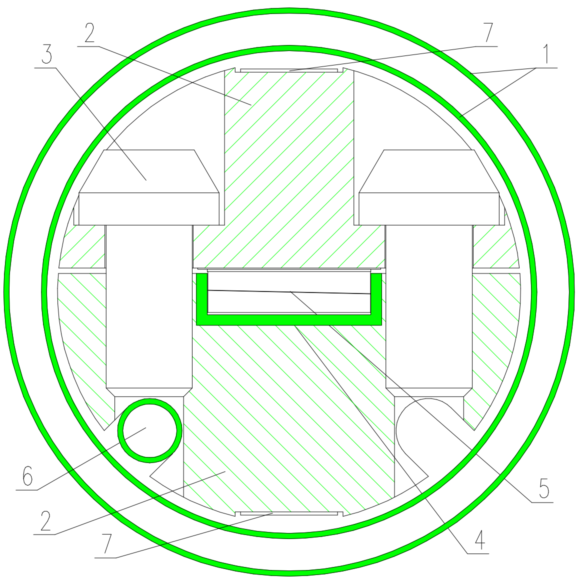

Fig. 2. Cross-section of the sample holder placed inside the bottom part of the inner cryostat. 1) Outer and inner vessel inner cryostat, 2) Stainless steel pressure bars, 3) M6 bolts, 4) U-shaped G10 fitting piece, 5) Sample consisting of: voltage tap package 1, sample 1, kapton insulation, sample 2, voltage tap package 2, kapton insulation, 6) Helium transfer line, 7) Heaters.

To ensure the proper position with respect to the applied field, the sample holder is locked in positions 0 and 90 degrees to the inner vessel of the inner cryostat by means of stainless steel keys, placed at both ends of the sample holder.

During a measurement an electromagnetic force acts on the bifilary cable sample, resulting in a maximum torque of 1000 Nm on the sample holder, being locked to the inner vessel of the inner cryostat with above mentioned stainless steel keys. In order to avoid torsion and possible damage of the sample holder and the inner vessel, this torque is transferred from the inner vessel to the outer vessel of the inner cryostat by means of G10 keys. This material is chosen for its very low conductivity-to-yield-strength ratio, implying that a given torque can be transferred with a minimum of thermal conduction between the two vessels. Moreover, benefitting from the thermal elongation of the inner cryostat, the full contact between the two vessels through the G10 piece is established only at low temperature (i.e. when doing measurements and the torque is present) while it is very small during warm-up, thus even further reducing the thermal losses. Measurements during the first cool-down resulted in a conduction loss smaller than a few Watt for a temperature difference between the two vessels of 300 K. Finally, the torque is transferred from the outer vessel to the outer cylinder of the magnet

To quickly warm up the inner cryostat for changing the samples, heaters are placed inside the 32 kA leads, onto the sample holder and inside the lower and upper baths, with a total available power of 4 kW.

E. Sub-cooled Superfluid Refrigeration Systems

The cooling to 1.9 K of the lower baths of both cryostats is achieved by two separate sub-cooled superfluid refrigeration systems. Each system comprises mainly a liquid-gas heat exchanger, a Joule-Thomson valve, a liquid-liquid heat exchanger and a vacuum pump. Liquid helium from the upper bath at 4.3 K is pre-cooled through the counter-flow liquid-gas exchanger made of stainless steel plates (located above the λ-plate), and expanded by the J-T valve in the copper liquid-liquid exchanger (located below the λ-plate), containing saturated liquid helium. By pumping directly on this exchanger, the lower bath of the cryostat is subcooled to 1.9 K while remaining at atmospheric pressure. The pumped helium gas passes through the counterflow liquid-gas heat exchanger pre-cooling the incoming liquid helium.

Both refrigeration systems are designed to have a maximum cooling power of ca. 15 W at 1.9 K, which is sufficient to guarantee a fast cool-down and compensate for the losses in the lower bath. These losses, consisting of conduction through the λ-plate and the feed-throughs and heat leak around the λ-plate, are estimated to be about 3 W for each cryostat. The cooling process can be regulated by the pumping speed of the vacuum pump and the opening of the Joule-Thomson valve.

F. Current Leads and Current Supplies

A pair of self-cooled 18 kA current leads is used to feed the magnet current into the outer cryostat. Each current lead has a loss of ca. 12 W at zero current and ca. 20 W at the maximum operating current of 14 kA. When the background magnet is not charged the helium level in the 4.3 K bath of the outer cryostat is kept to below the bottom connector of the current leads, hereby further reducing the 0 A loss.

A pair of self-cooled current leads optimised for 24 kA operation with the possibility to run up to 32 kA for a short time will be used to feed the sample current into the inner cryostat. The design is based on the experience obtained with similar current leads fabricated using the same technology [6]. Each lead consists of a stack of 80 copper finned sheets of 910 mm length, 0.5 mm thickness and 40 mm width. Over most of the surface of the sheets a layer of 0.25 mm is chemically etched away, to form a staggered arrangement of buttons, giving a very large surface contact area and enabling the He gas to flow through.

Inside each current lead 4 temperature sensors and 2 voltage taps are placed to verify during operation the temperature distribution along the lead and to protect the lead against burn-out. The helium gas flow through each current lead can be individually regulated using a control valve in order to minimise the helium consumption.

Both pairs of current leads are connected via water cooled leads to two current supplies, made with a modular concept with 4 respectively 8 current sources of 4 kA, 6 V in parallel [5]. The 4 kA sources contain a diode rectifier on the AC mains with a damped L-C filter, a zero voltage switching inverter working at 20 kHz and an output stage (high frequency transformers, Schottky rectifiers and output filters). The currents will be regulated and measured using one respectively two 16 kA DCCT's with a precision better than 10^{-4}.

The magnet and sample circuits (including the current leads) are protected against overheating by a 10-channel quench detection system. In case of a magnet quench, its energy is almost fully extracted by bypassing the current through a dump resistance of 20-40 mΩ using a mechanical switch.

III. Instrumentation

A. Voltage Tap Package

On the outer side of each sample a voltage tap package is mounted. Such a package is made of a ca. 2.2 m long kapton foil on which copper tracks (with thickness of 35 µm and width of ca. 1 mm) are printed acting as voltage taps. The taps cover the whole width of the cable so that the measured voltage is close to the average cable voltage (since the resistance of the voltage tap over the width is small compared to the resistance between the strands and the voltage tap). Each voltage package has 7 pairs of voltage taps, enabling the measurement of several *U-I* curves on different lengths of the samples. The 14 voltage signals are measured by two Keithley nV meters via two eight channel nV scanner cards.

B. Hall Probe Signals

Two arrays of 26 Hall probes will be installed on one edge of each cable in order to measure the self-field of the cable. The distribution of the self-field along one cable pitch makes it possible to estimate the distribution of the transport current among the strands. A non-uniform distribution can be related to a significant lower I_C-value in one or more strands, or to a non-uniform resistance in the connections on either side of the cable. The 52 Hall probe signals will be measured using a 64 channel datalogger.

C. Temperature Measurement

A total of 25 Platinum and 13 Cernox 1050 sensors are used to monitor the cool-down and warm-up of both cryostats. As the reference temperature for the I_C-measurement a Cernox 1050 sensor in combination with a Germanium sensor is used. Both sensors are placed in zero field and calibrated to 5 mK accuracy. A possible temperature variation along the 2 m long sample holder is measured by 4 Cernox 1050 sensors.

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