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FIRST COOL-DOWN AND TEST AT 4.5 K OF THE ATLAS SUPERCONDUCTING MAGNET SYSTEM ASSEMBLED IN THE LHC EXPERIMENTAL CAVERN

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First cool-down and test at 4.5 K of the ATLAS superconducting magnet system assembled in the LHC experimental cavern

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INTRODUCTION

ATLAS, a 7000 t detector for elementary particles [1], is the biggest experiment at the Large Hadron Collider (LHC) at CERN now in advanced stage of hardware commissioning prior to the injection of the first proton beams.

For accurate measurements of the momentum of the elementary particles produced in the 2x7 TeV energy collisions of the LHC beams, the ATLAS collaboration has adopted a magnetic configuration generated by four superconducting magnets cooled at 4.5 K: one Central Solenoid (CS, see Figure 1), one Barrel Toroid (BT, see Figure 2) and two End-Cap Toroids (ECT, see Figure 3). The choice of the superconducting solution was imposed by reason of economy and “transparency” to the particles emerging from the beam collision point.

The CS [2] provides a longitudinal 2 T magnetic induction for the inner silicon tracker and the three toroids [2] generate a tangential field of about 1 T (with a peak field of 4 T near the conductor) for the external muon spectrometer surrounding the entire detector. The overall dimension is 22 m in diameter and 26 m in length with a total mass at 4.5 K of 680 tons. The stored electromagnetic energy in the toroids powered at 20.5 kA current is 1.1 GJ for the BT and 0.5 GJ for the two ECTs. The CS has a 5.5 t cold mass with a stored energy of 39 MJ at nominal 7.7 kA current. In the fast energy dump mode of the toroids all the energy is discharged into the cold mass by provoking via heaters a simultaneous resistive transition of the coils. The corresponding average temperature rise of the cold mass stays below 60 K.

Figure 1 Central Solenoid

The BT magnet is made of eight racetrack coils housed in separate vacuum vessels. A central cryogenic ring subdivided in eight sectors provides the internal cryogenic, electrical and vacuum interconnections. External feedthroughs, electrical and cryogenic are connected to the top sector. The two (A and C) ECTs have identical design and are made of eight coils housed in a common vacuum vessel. Each ECT is equipped with a turret for cryogenic, electrical and vacuum connections to the external supplies. The CS is housed in the vacuum vessel of the barrel liquid argon calorimeter and has an independent chimney for the cryogenic and electrical supplies.

To be ready for first particle collisions in the LHC, the ATLAS magnets with their associated helium cryogenic system are undergoing an intense test campaign.

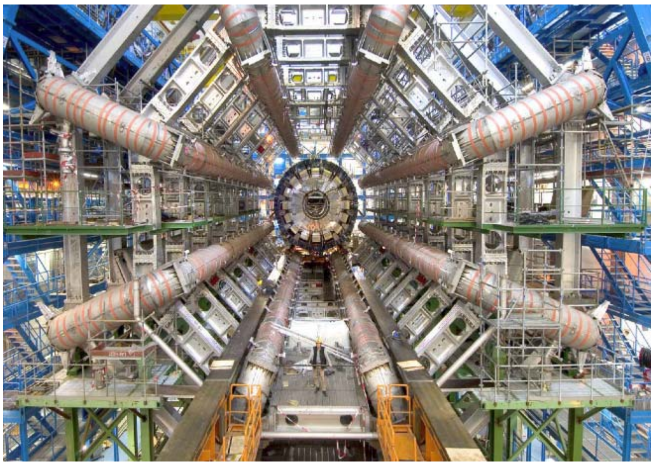

Figure 2 Barrel Toroid

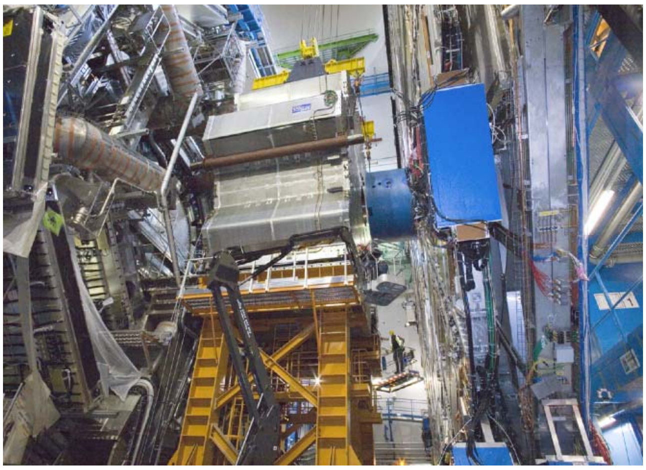

Figure 3 End-Cap Toroid

BASIC DESIGN OF THE CRYOGENIC SYSTEM

The simplified flow scheme of the ATLAS magnet refrigeration system is shown in Figure 4.

The helium refrigerators

The cooling capacity is generated by two independent helium refrigerators [3] installed in a service underground area near the main cavern housing the ATLAS detector.

The Main Refrigerator (MR) of nominal 6 kW @ 4.5 K capacity keeps the magnet cold mass at 4.5 K and cools the current leads whilst the Shield Refrigerator (SR) of 20 kW @ 60 K takes the load from the thermal shields and can be boosted by liquid nitrogen up to 60 kW during the cool down phase from ambient temperature to 100 K. The MR uses five compressors, 500 g/s total flow at 1.8 MPa, and three expansion turbines. The SR uses two compressors, one redundant each supplying 150 g/s at 1.8 MPa, and two turbines. The total maximum electrical power input is 3.6 MW. The MR supplies saturated liquid at 0.16 MPa and the SR 40 K gas at up to 1.8 MPa.

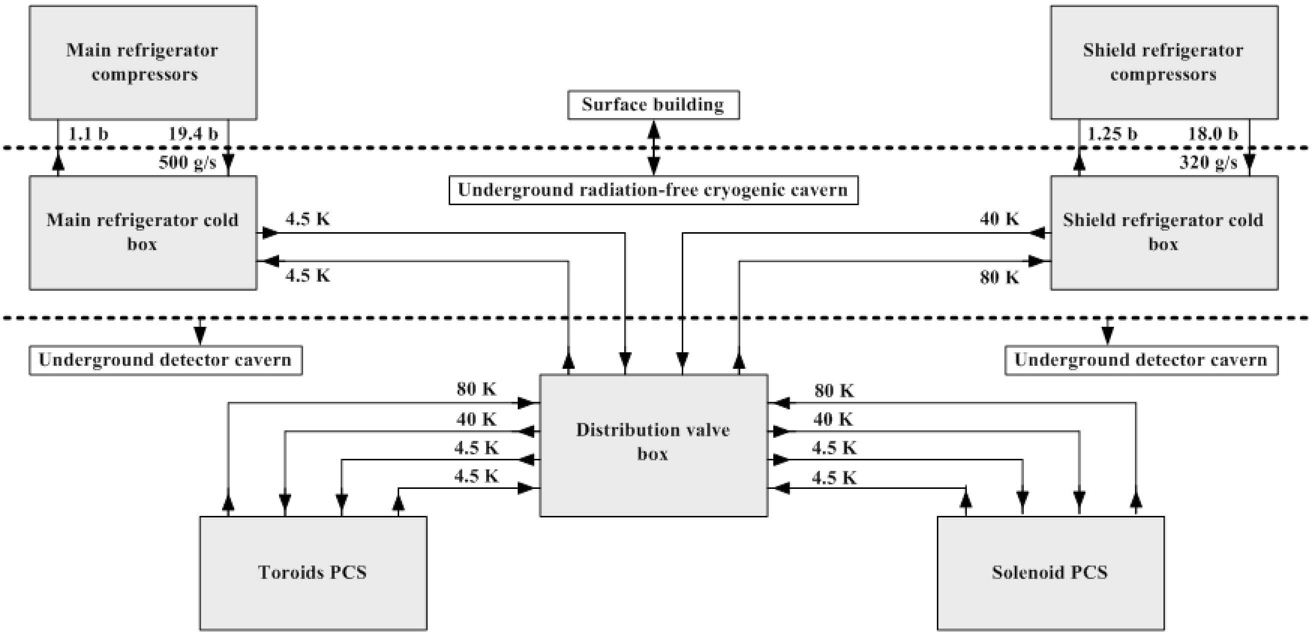

Figure 4 Basic flow scheme of the ATLAS magnet cryogenic system

Transfer lines and proximity cryogenics

The liquid and cold gaseous helium generated by the two refrigerators is transferred via an 80-m long line to a Distribution Valve Box (DVB) sharing the flow to two separated sub-systems [4, 5] called Proximity Cryogenic System (PCS). One PCS in common for the three toroids and the other PCS dedicated to the solenoid. The toroid's PCS is located near the cavern wall at a distance of about 20 m from the top centre of the detector. It is equipped with a unique facility that allows, by means of "drag chains" driving flexible transfer lines (4 coaxial lines each 17 m long), to move both ECT's cryostats by several meters to their parking position while still at nominal cryogenic operating conditions. The solenoid's PCS, located at the top of the detector, is fixed and connected to the CS via a 10 m long chimney.

The key components of the toroid's PCS are two centrifugal pumps (one redundant) each providing 1200 g/s flow at 40 kPa pressure head with an efficiency (hydraulic/shaft power) of 60 % [6]. Liquid helium is sucked from the bottom of a phase separator (4600-litre capacity) kept at 0.13 MPa and distributed to ten parallel lines, one per each BT coils and one per each ECT. Liquid overflow in each circuit is driven back to the phase separator whilst the gas produced in the magnets is returned to the MR cold box or can be routed, via the SR low pressure line (vacuum insulated) and an atmospheric heater, to the suction of the SR compressors for discharge into the buffer vessels. The PCS distributes the gaseous helium supplied by the SR to the shields via three lines, one for the eight BT coils and one for each ECT. By-pass valves allow the connection of the SR to the MR circuits for cooling down of the magnet cold masses in parallel to the shields. Additional valves isolate the return circuits of the magnets from the PCS system for its warm-up independent from the cold masses. The toroid's PCS includes 33 cryogenic valves.

An additional important facility is an 11000-litre capacity back-up dewar that can automatically provide liquid to the phase separator for allowing the slow energy dump of the toroid magnets in case of stop of the MR. The evaporated gas is recovered by the redundant SR compressor via the vacuum insulated low pressure line. If also the SR is stopped, an automatic restart of its compressors is implemented to minimize helium venting to atmosphere.

The solenoid's PCS has a more simple design and allows two cooling modes: a two phase helium flow forced by the refrigerator and a thermo-siphon mode to be used for the slow dump of the current in case of MR failure using the back-up of the helium contained in the phase separator of the thermo-siphon. It includes 10 cryogenic valves.

The combined system MR, SR and the two PCS were designed for cooling from 300 K down to 4.5 K of the solenoid with the toroids at their operating conditions. On the contrary the three toroids are considered as a single cold mass and cool-down of one toroid in parallel to the operation at 4.5 K of another one is not possible. The same is valid for the CS that cannot be operated at 4.5 K during the cool down of the toroids.

The internal cryogenics

All the magnets are cooled by the indirect method with aluminium pipes glued (BT) or welded (ECTs) to the aluminium alloy casing embedding the double pancake windings and to the external mandrel of the CS supporting the single layer coil wound. Superinsulated aluminium thermal shields cooled by gaseous helium surround the cold mass of the toroids. For the CS, the inner thermal shield is also cooled by gaseous helium whilst the outer shielding is provided by the liquid argon calorimeter operated at 88 K.

Superinsulation is also wrapped around the coil casing of the BT and of the CS mandrel. A 6 K shield of the ECT's coils in thermal contact with the keystones has been implemented. Heat intercepts at the temperature level of the shields was applied to the tie rods and the "cold stops" of the 4.5 K mass of the toroids.

Cooling is carried out in parallel by means of (2x8) per coil x 8 coils = 2x64 pipes for each toroid, one of the two circuits is redundant for possible use in case of a helium leak in the other one. The CS is equipped with two parallel serpentines, one at each side of the mandrel. Orifices with flow impedance larger than that one of the corresponding toroid circuits were implemented to prevent potential dry-out of a circuit or to compensate for unbalance in the hydraulic impedance. Similar distribution with orifices to compensate for flow unbalance was adopted for the pipes cooling the thermal shields.

Subcooled liquid helium at 0.17 MPa is supplied by the pump to the BT and the ECTs and is returned as two-phase into the PCS phase separator. For hydraulic stability the cooling system of the three toroids was designed to fulfil two conditions: a specific mass flow rate higher than 4 $g.s^{-1}.cm^{-2}$ and a gas mass fraction at the outlet of each circuit less than 10 %. For the CS, having a much simpler geometrical pipe distribution, the saturated helium flow at 0.16 MPa from the MR is first subcooled by a heat exchanger immersed in the phase separator of the PCS kept at 0.13 kPa and then routed to the cooling serpentines. The flow is adjusted in a way to assure, by a heater in the same return phase separator, that the cooling pipes are wet all along their length.

CRYOGENIC OPERATION AND TEST RESULTS

Individual cool-downs and tests

The eight coils forming the BT were individually tested at ground level at their nominal operating conditions in a dedicated facility [7] prior to their underground installation. The same procedure was adopted for the CS tested at ground level after insertion in the final cryostat housing the liquid argon calorimeter. For reasons of schedule, the two ECTs passed only an electrical isolation and mechanical integrity test at liquid nitrogen temperature without being equipped with their turrets which were mounted later in the underground area.

After transport and final assembly in the ATLAS cavern, the four magnets were connected to the cryogenic system and individually tested [8, 9] in a sequence following the detector installation progress. The BT and the CS were powered at nominal current whilst the ECT-C and ECT-A passed a partial test in the “parking” configuration at respectively 15 kA and 10 kA prior to their move to the final position close to the BT.

Final cool-down and steady-state operation

The use of the SR and the MR for respectively the 300 K-to-100 K and 100 K-to-4.5 K temperature ranges allowed a considerable operational flexibility during the powering test campaign of the magnets. At the exception of the CS, the three toroids, after passing a 4.5 K test, were maintained at low temperature by cooling the associated thermal shield with the SR and starting sequentially the next test with the MR. Even during the annual shut-down period required for maintenance, the maximum temperature of the cold mass never exceeded 150 K thus minimizing the thermal cycling. The final cool-down from 120 K to 4.5 K was carried out with all the toroids in parallel (see Figure 5) whilst the CS, having much less cooling power requirements, was cooled from 300 K to 4.5 K at a later stage keeping the toroids in the operating conditions.

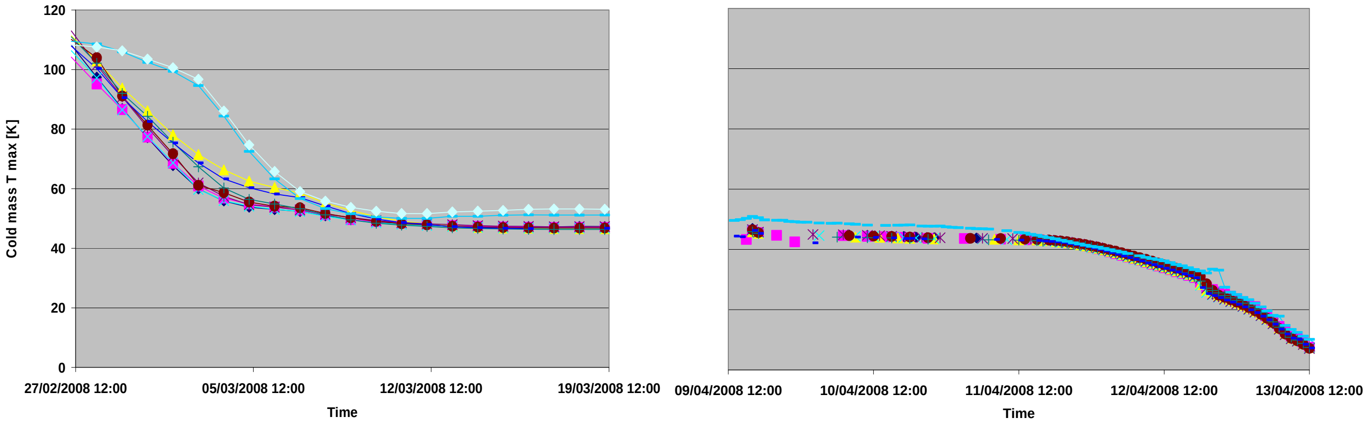

Figure 5 Cool-down in parallel of the BT and the two ECTs: left graph by means of the SR, right graph by means of the MR ready for operation after 20 days (the time gap between the two graphs)

At the end of the cool-down, the liquid supplied in parallel to the coils by the MR reaches the PCS phase separator and fills it up to a predefined level allowing the start of the pump. A similar procedure is adopted for the CS without the use of the pump. The combined system MR + the two PCS + the pump has reached a good pressure/temperature stability of ± 0.3 kPa in the corresponding phase separator and

a very stable flow distribution as judged by the liquid flow indicators installed at each return line (see Figures 6, 7). When the magnets are not powered, a liquefaction load is maintained by routing via a by-pass valve 4.5 K gas to the vacuum insulated suction line of the SR compressors.
This valve actually controls the level of the liquid in the MR phase separator thus keeping a constant balance between refrigeration and liquefaction capacities.

During the ramp-up of the magnet current with consequent increase in the liquefaction demand for cooling the four pairs of current leads (one for each toroid and one for the CS), the by-pass valve closes keeping the MR in the same operational configuration.

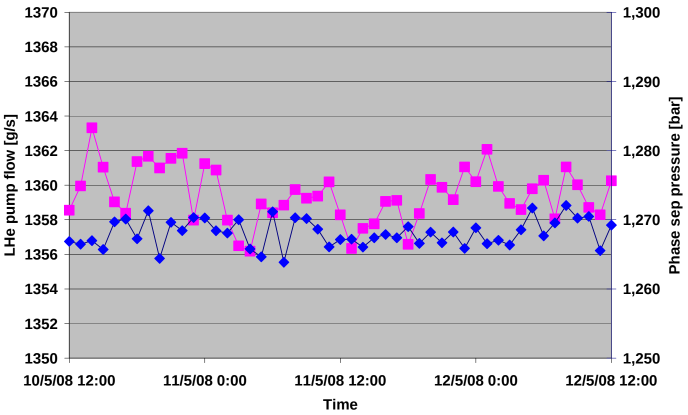

Figure 6 Pressure (rhombi) stability in the PCS toroid's phase separator and pump mass flow rate (squares)

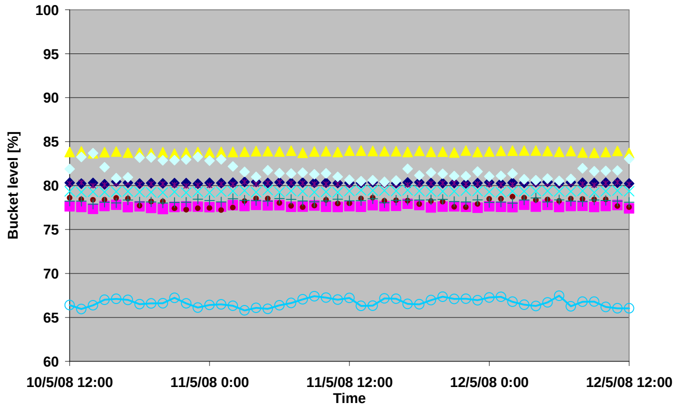

Figure 7 Stability of liquid helium flow indicators at the outlet of the cooling circuits of BT and ECTs

Measured thermal balance of the entire system

The isothermal refrigeration load at 4.5 K of the entire cryogenic system is 1700 W measured with an average shield temperature of 55 K. The total heat load on the shields at the same average temperature is about 10 kW.

The magnets with their associated components (cryogenic ring, chimney, turrets, current lead cryostats and transfer lines up to the corresponding two PCS systems contribute for 48 % of the total load (510 W for the BT, 290 W for the two ECTs and 17 W for the CS). The pump at the operating conditions contributes for 39% (670 W) and the remaining 13% (215 W) of the load is due to the PCS, DVB and transfer lines system (165 W for the toroid's PCS, 10 W for solenoid's PCS, and 40 W for DVB and transfer lines).

The current leads at nominal operating current required 1.85 g/s x 6 (for the toroids) +1 g/s (for the CS) = 12.1 g/s and the MR operating parameters were set with the full refrigeration load of the system at a liquefaction capacity of 14.9 g/s thus giving 23 % margin in liquefaction.

Dynamic heat load and recovery from energy fast dump

In addition to the static heat load, eddy currents induced in the coil casings during ramp-up and down of the magnets, generate a dynamic load.

The final powering of the three toroids electrically connected in series was delayed because a helium leak appeared in an electrical insulator of one of the cooling circuits of the ECT-A current leads. Individual tests at nominal current were carried out for the BT, the ECT-C, the CS and very recently the BT and the CS were powered at the same time (see Figure 8). Dynamic heat loads measurements during the slow dump were, therefore, only partial giving respectively at the start of the current discharge: 360 W for the BT, and 25 W for the CS. The ECT-C was discharged from 20.5 kA only in the fast mode. Normal discharge time for the toroids is about 2 hours and 30 minutes for the CS.

During the fast energy dump, the MR is disconnected from the PCSs and the pressure builds up in the corresponding phase separators which are large enough to contain the liquid expelled from the magnet circuits. The cold gas is routed via the MR bypass valve, to the low pressure of the SR starting the redundant compressor. In this way the pressure increase is smoothed. During the individual fast dump of the BT and ECT-C the pressure was kept below 0.6 MPa and 0.3 MPa respectively avoiding any discharge into the atmosphere. In the case of the CS the pressure rise was 0.7 MPa but no gas dump from the SR was used.

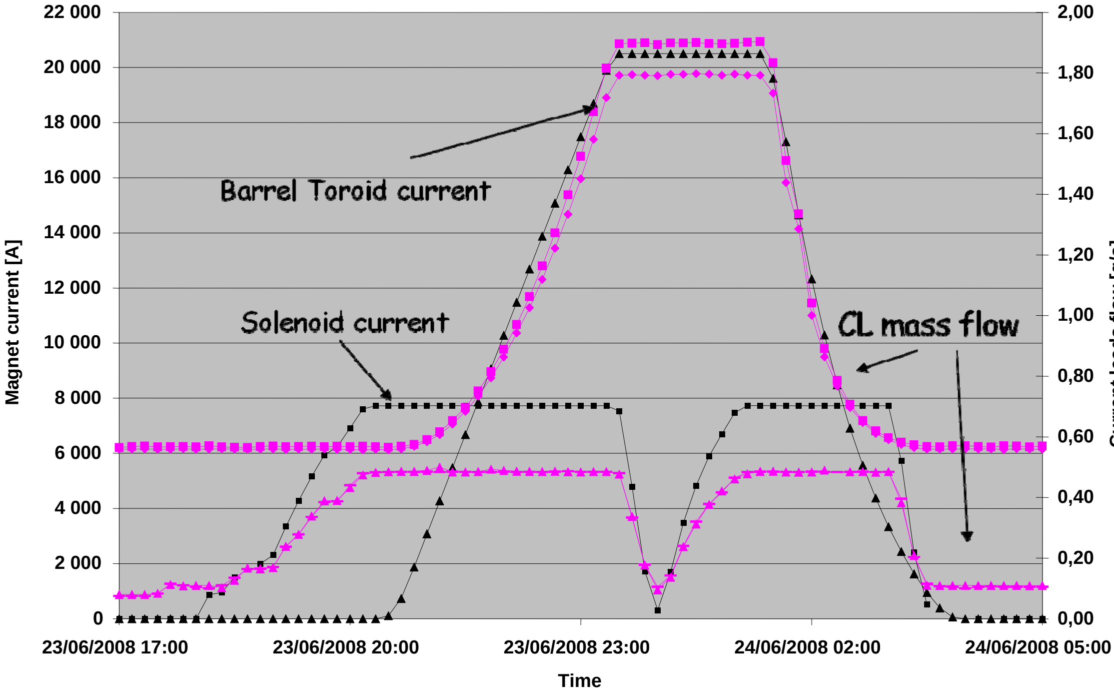

Figure 8 Powering of the BT and the CS at their nominal current of 20.5 kA and 7.7 kA respectively. The graph shows the helium flow cooling the current leads (right scale)

CONCLUDING REMARKS

The magnetic system of the ATLAS detector is in the final phase of test prior to its long term use for LHC physics. Powering of the three toroids electrically connected in series is planned for August 2008.

The cryogenic system has been operated successfully with all the magnets cooled in parallel at 4.5 K and showed the desired flexibility during the complex operating modes required by the test program of the magnets.

A complete thermal analysis was carried out and the measured values are in accordance with the design values [3]. A sufficient margin of cooling capacity is expected once the current leads will be powered simultaneously fully loading the refrigerating system.

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