COMMISSIONING AND FIRST OPERATION OF THE LOW-BETA TRIPLETS AND THEIR ELECTRICAL FEED BOXES AT THE LARGE HADRON COLLIDER

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ABSTRACT

The insertion regions located around the four interaction points of the Large Hadron Collider (LHC) are mainly composed of the low-β triplets, the separation dipoles and their respective electrical feed-boxes (DFBX). The low- β triplets are Nb-Ti superconductor quadrupole magnets, which operate at 215 T/m in superfluid helium at a temperature of 1.9 K. The commissioning and the first operation of these components have been performed. The thermo-mechanical behavior of the low- β triplets and DFBX were studied. Cooling and control systems were tuned to optimize the cryogenic operation of the insertion regions. Hardware commissioning also permitted to test the system response. This paper summarizes the performance results and the lessons learned.

KEYWORDS: LHC, superconductors, low-β triplets, electrical feed-boxes, applied superconductivity.

INTRODUCTION

The low-β magnet systems of the Large Hadron Collider (LHC) were designed and constructed by a world-wide collaboration since 1998. They are installed at each interaction point (IP) of the LHC [1]. They provide the final focusing of the proton beams before collision. This paper describes the low-β magnet systems, gives the headlines of the hardware commissioning and lists several non-conformities that were the object of consolidations during the commissioning period 2007 through 2008.

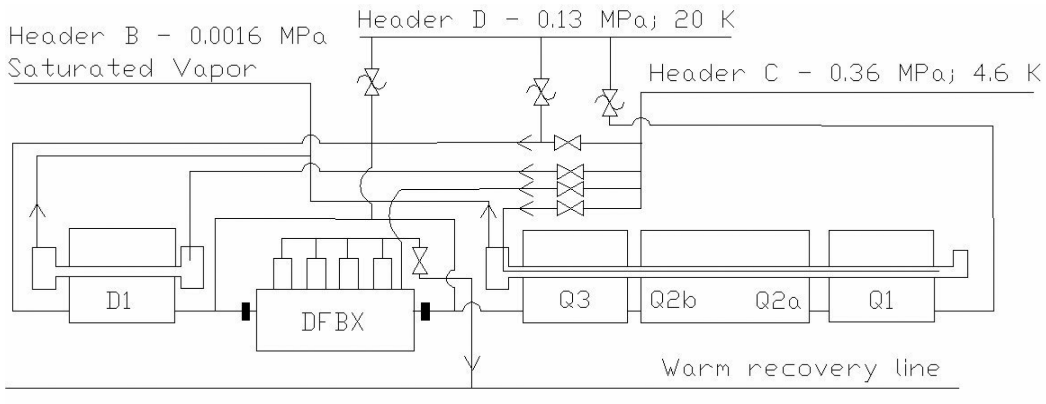

FIGURE 1. Flow schematic of the inner triplet, D1 and DFBX at IP5 and IP8

DESCRIPTION OF THE LOW-BETA MAGNET SYSTEMS

The low-β magnet systems are composed of an electrical feed box (DFBX), four 70 mm aperture quadrupole magnets (Q1, Q2a, Q2b, Q3) so-called the inner triplet, a beam separation dipole magnet (D1), and five corrector magnet assemblies. The D1 is superconducting at the low luminosity IPs (IP2 and IP8) or conventional at the high luminosity IPs. A typical low-β flow scheme with a superconducting D1 dipole is shown in FIGURE 1. The superconducting magnets operate at a temperature of 1.9 K and a pressure of 0.12 MPa. The DFBX current leads cold terminals operate in saturated liquid helium and are separated from the inner triplet and D1 superfluid helium baths at 1.9 K by lambda plugs. Each magnet is equipped with cryogenic instrumentation, control valves and quench heaters, which can provide up to 100 W. Current leads, bus work and magnets are instrumented with voltage taps.

The DFBX assembly Maximum Allowable Working Pressure is 0.35 MPa. It is connected to a 2.0 MPa MAWP equipment and its associated cryogen distribution lines. It powers the superconducting low-β magnets and also provides the cryogenic environment needed by the current leads.

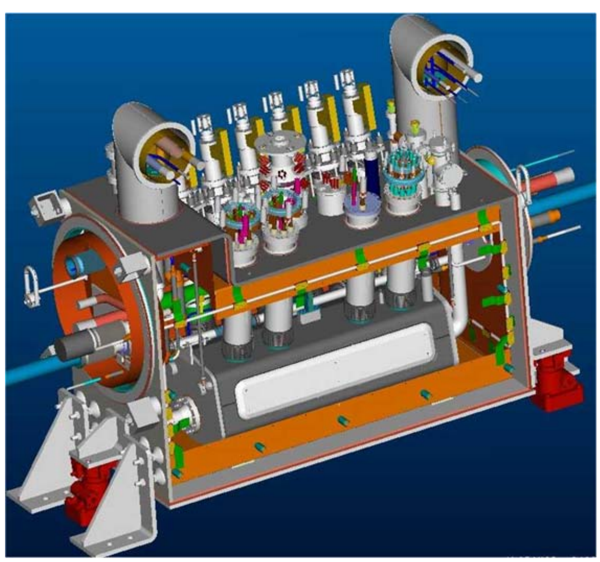

FIGURE 2. CAD model with the connections to the distribution lines

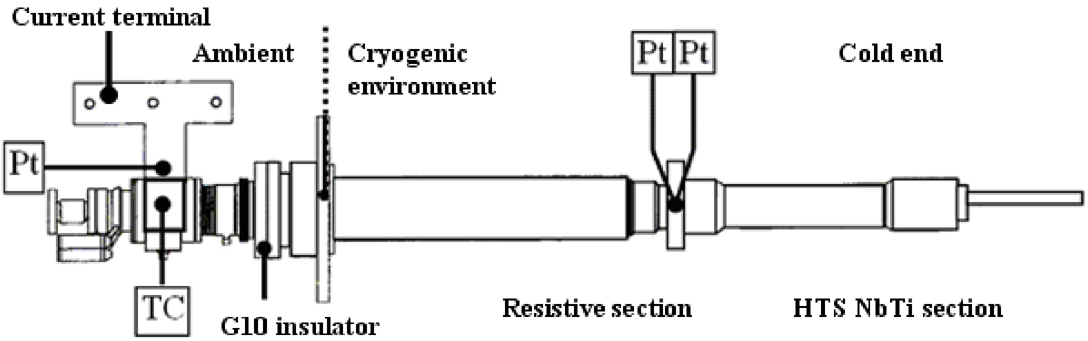

FIGURE 3. 7.5 kA HTS current lead with cryogenic temperature sensors (Pt100 and Thermocouple).

The DFBX is mainly composed of a helium vessel, thermal shield, vacuum vessel, valves and instrumentation, safety components, and current leads of 7.5 kA, 600 A and 120 A ratings. The six (or four for high luminosity IPs) bottom parts of the 7.5 kA current leads are made of HTS material, while the fourteen 600 A and the ten 120 A current leads are entirely resistive. FIGURE 2 shows a 3-D view of the DFBX with the connections to the cryogen distribution lines. The vapor cooled leads and connections to the distribution lines are not visible.

FIGURE 3 shows a schematic view of a 7.5 kA HTS current lead and its temperature sensors. In stand-by and powering conditions the temperature at the warm and cold end of the HTS current leads is maintained at 50 K. The upper section of the lead is a conventional gas-cooled resistive lead, cooled by a gaseous helium flow, which enters the lead at a nominal temperature of 20 K.

Each 7.5 kA, 600 A and 120 A leads are equipped with a 350 W, 35 W and 20 W flag heaters, respectively. This heater permits warm up of the cold helium gas flow to the ambient temperature before venting it to the WRL. The heater is locally controlled by a thermocouple.

The 120 A and 600 A resistive leads are cooled by vapor boiling out the helium tank. The ten 120 A leads are collected on one chimney, whereas the fourteen 600 A leads are distributed on three chimneys.

FROM CRYOGENIC COMMISSIONING TO FIRST OPERATION

The commissioning was performed together with the whole LHC cryogenic system as the refrigerators and distribution of all cryogenic equipment of a sector are common. Cryogenic commissioning started once every process circuits was closed, leak checked, pressure tested and flushed. The commissioning process consists of several phases during which all the instrumentation and components are progressively tuned to control the required levels of temperature, pressure, liquid level or flow [3-4]. The following sections present the different phases observed before the first LHC accelerator operation and proton injection.

Preparation to Cool-Down the DFBX

The low-β magnet systems were assembled in the tunnel and pressure tested [5]. The test sequence for the commissioning of the DFBX was [6-8]:

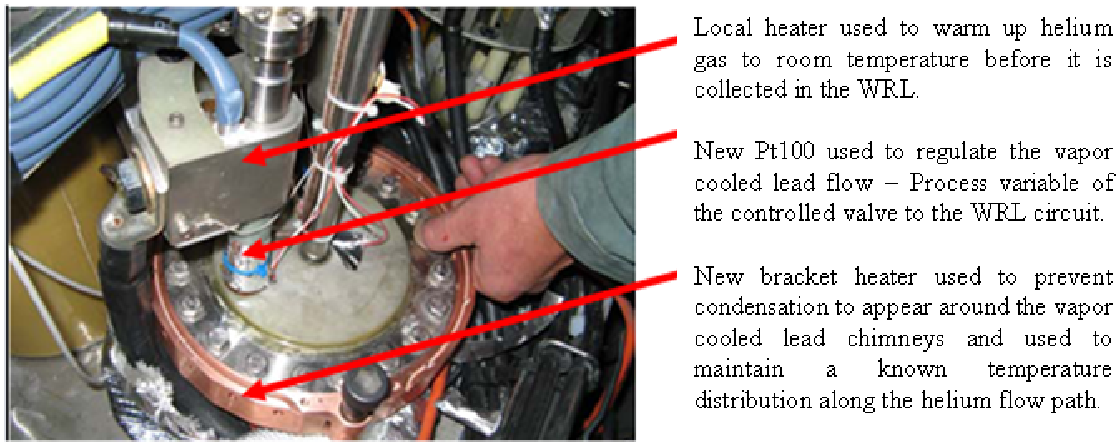

FIGURE 4. Chimney containing two 600 A vapor-cooled leads, showed with its new bracket heater and Pt100 temperature sensors.

- Before tunnel installation, G-10 surfaces of the 7.5 kA HTS power leads had been properly coated with silicone and polyurethane to prevent moisture-related issues.
- Leak test and continuity verification of the heater power and instrumentation were completed after the components were connected in the tunnel.
- Interlock systems (pressure switch, temperature to interlock distribution line voltage taps connected to the correct circuits) were checked.

Low–β Magnet System Cool-down and Powering Preparation

The low-β magnet system cool-down procedure is described in [2]. Whereas the first low–β magnet cool-down of the sector S78 took 2 weeks, the typical low–β magnets cool-down time is now four days from room temperature to 4 K. Since they are located at the extremity of the LHC accelerator sector cooling string, the cool-down rate is quite high (3 K/h). In order to optimize the cooling capacity and the low-β magnets supply pressure, the low-β magnets and the DFBX are cooled separately from 300 K to their operating temperatures. The relief pressure for the low-β magnets is the same as for the arc magnets, i.e. 1.7 MPa. The mass-flow used during the cool-down is determined by the average cell temperature and the total helium capacity available in each arc.

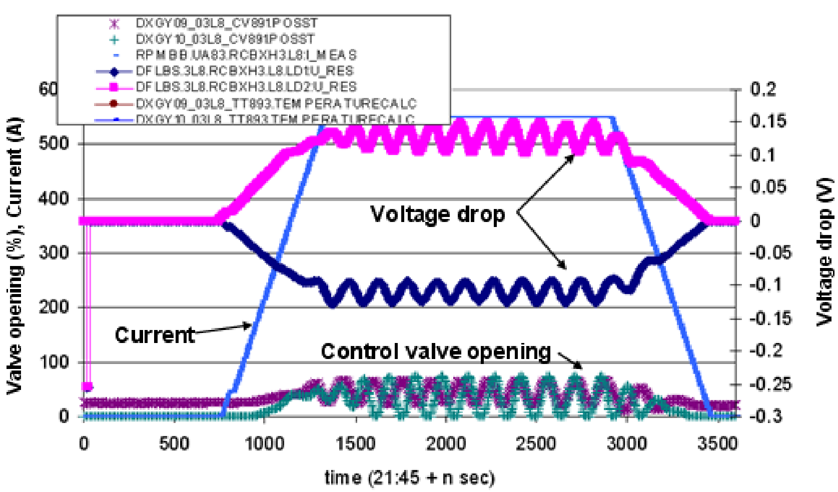

FIGURE 5. Evolution of vapor cooled lead circuit temperatures and valve opening during a current ramp up.

Criterion to determine the cool-down rate is a limit of 150 K in the temperature difference between the cooling cell helium supply and return. From the cool-down control logic point of view, the main difference between the low-β magnets and the arc cell magnets is their mass. The low-β magnets and the typical LHC continuous ARC-cell magnets weights are 32,903 kg and 356,000 kg, respectively. This implies that the cool-down time is 10 times faster for the former than for the latter for given temperature and pressure differences. The low-β magnets commissioning is further documented in [3-8]. The in-situ calibration of the IT magnet Cernox thermometer was performed by checking the Lambda transition.

Once the low-β magnets and DFBX are filled with liquid helium, a boil-off test permits us to verify the different level gage geometric positions and the operating cryogenic parameters (e.g. set-points for controlled valves and heater). Then, all electrical circuits are tested through the quality insurance process before being released for powering.

DFBX Vapor Cooled Lead Parameters Tuning during Powering

During the electrical circuit powering phase, we needed to tune the operating parameters of the 600 A and 120 A vapor cooled leads. Since the operating ranges of the control valves were initially inadequate, the controller electronics had to be tuned ring-wide to provide a typical operation of 20 % at full current. Each resistive leads cooling was completed by tuning the PID parameters of their associated control system. FIGURE 5 shows the control valve openings and voltage tap stabilization during the ramp up to the maximum lead current. The control valve opening follows the lead flag temperature.

This tuning permitted us to identify limits in the lead cooling capacity. For instance, the vapor cooled lead acceptable voltage drop trip point was raised from 100 mV to 160 mV. Above this threshold, the QPS system will stop the lead excitation at the source.

Plus, future LHC physics requirements demand reducing the collapsing time of the proton separation bumps from 40 second to the minimum achievement time. For that purpose, the Q1 and Q2 corrector dipoles, so called MCBX, needs adjustment of the ramp and acceleration rates. The current specification calls for a ramp rate of 5 A/s and an acceleration rate of 0.5 A/s^2, values which were validated before the first injection on September 10^{th} 2008. Since the MCBX are powered by the 600 A vapor cooled current leads, the feasibility of large ramp and acceleration rates is being investigated.

Ultimate Heat Load Extraction – Capacity Test

A total of 46 W of static heat load was measured for the low-β magnets located left of IP8 [4].

The maximum power to be extracted from each low-β magnets was determined using electrical heaters attached to the low-β magnets. The theoretical power limits are given by 1) the local two-phase flow-pattern with the corresponding wetted heat exchanger surface and by 2) the vapor velocity which has to be less than 7 m/s to prevent liquid being carried away by the vapor stream. Measurements done in low-β magnets located right of IP2 showed we can extract 366 W (320 W heater power + 46 W estimated static heat load).

During these measurements, we noticed that the cold compressor operation can be affected by the cryo-system behavior under transient conditions if extra liquid phase of the sub-atmospheric He II cooling flow is not properly burned in the bayonet heat exchanger accumulator before the gas returns to the cold compressor (see chapter on the consolidation of passive heaters).

CONSOLIDATIONS AND NON-CONFORMITIES

DFBX Vapor Cooled Lead Control System

The temperature of resistive vapor cooled leads was specified to be controlled by a flowmeter, which during commissioning was found to be too inaccurate to permit the use of such a control variable. Unfortunately, no appropriate radiation resistance flowmeter was readily available and the addition of temperature sensors on the cold end leads (typical control variables for the HTS leads) would have taken months of down-time on the Hardware Commissioning Schedule. As an alternative solution, the existing control system was redesigned and implemented without opening the DFBX. Each of the 24 leads of the eight DFBX was modified to accommodate new flexible temperature sensors. These new Pt100 sensors permit us to individually monitor and regulate the controlled valves, which provide helium cooling to the vapor cooled leads. FIGURE 4 shows the temperature sensors installed on the G10 electrical insulator of every lead. This location was the coldest accessible place able to monitor the flow temperature. The density of equipment on the top of the DFBX made this task delicate but possible. The controlled and monitoring process using the cryo-PLC via PVSS was modified in order to integrate the given hardware [9]. A total of 192 new control loops are currently successfully operating and properly controlling the lead flows and temperatures.

DFBX Water Condensation Issues

After several days of operation with DFBX filled with liquid helium, water condensation and ice were observed around the vapor cooled lead chimneys. This phenomenon driven by the LHC tunnel dew point and current leads' limited thermal insulation was previously observed on the arc DFB. For the DFB, a dry-air circulation system was implemented and installed in 2008. A similar solution was unrealistic in the case of the DFBX, due to space constraints. The alternative solution to resolve this issue was to install a bracket heater around each vapor cooled lead chimney's flanges in order to maintain a constant temperature profile. Two 180 W heater cartridges were inserted in every chimney copper bracket. Local controllers were implemented to regulate the bracket temperatures. A total of 32 heating elements are currently operating.

Similarly, water condensation was observed on the top plate of the DFBX at the proximity of HTS lead chimneys. In this case resistive heaters have been wrapped at the bases of the HTS current leads and a thermometer regulates the DFBX top plate temperature above the dew point.

Installation of Electronic Filters

An offset in the measured temperature of the 600 A vapor cooled lead was observed between the field measurement and the control system read-out [10]. The cause of the offset was identified to be an electronic noise caused by local electronics floating with respect to the ground. This off-set was removed by implementing a 4.7 µF capacitor per temperature channel. Twelve capacitors are grouped in one so-called filter-box, which is directly plugged into the instrumentation connector of the DFBX. FIGURE 6 shows the difference of signal read back without and with the new capacitors installed. The off-set with the local resistance measurements disappeared, i.e. the noise is properly filtered and the real temperature values are now achievable using the cryo-PLC.

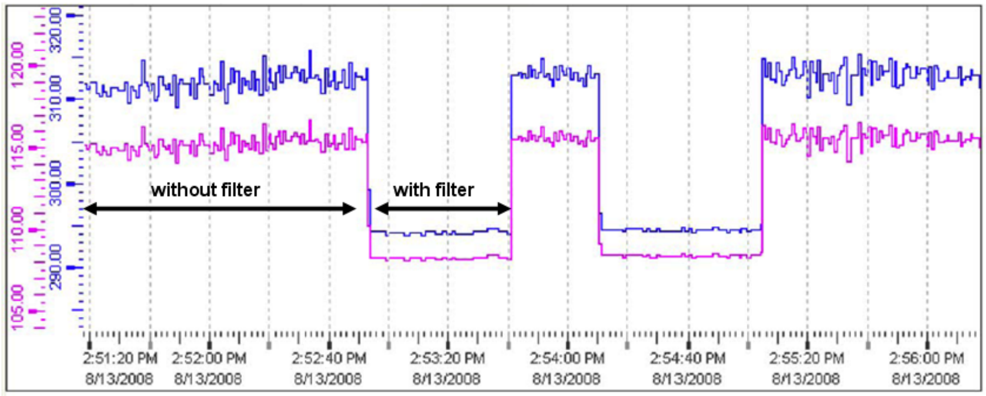

FIGURE 6. Temperature and resistance measurements without and with the filter installation.

Passive Heater on the Low-β Magnet Sub-Atmospheric System

The phase separator pot located at the extremity of the inner triplet magnet bayonet heat exchanger accumulates the non-used liquid from the saturated helium flow circuit. Passive heaters, made of two copper braids, are needed to vaporize the residual liquid helium. In the presence of liquid, via a pipe, a thermal link to the copper braids becomes active and a total of 122.5 W can quickly evaporate the non-used liquid. This passive action prevents the counter-flow heat exchanger through which the vapor returns to the QRL to become blocked by liquid, and as well the cold compressor to trip if liquid helium were to flow towards its inlet. The passive heaters were supposed to be installed on the Q1 accumulator only when Q1 is at the highest point (LHC tunnel) of an inner triplet. During the hardware commissioning of the low-β magnets, it was observed that passive heaters were systematically mis-installed, generating extra static heat load for half of the inner triplets and risking liquid fill of the counter-flow heat exchanger for the other half.

Following the capacity test and field investigation, we identified that only two of these eight non-conformities, those at high luminosity points, needed to be fixed; the other cases could be dealt with by specific cryogenic operational measures because they never see a very high heat load. We used the opportunity of the IT cryostat opening required by the given consolidation, to modify two temperature sensors at these two locations [11].

Installation of Pressure Relief Valves

Following the updated evaluation of the Maximum Credible Incident (MCI) caused by the September 19^{th} incident, three pressure relief valves were added on each interconnection of the low-β magnets. Three existing 63 mm diameter parallel plates remain active above 100 mbar. The 200 mm diameter relief valves are sized to release safely up to 20 kg/s of helium at 10 K [12-13]. Deflectors are used to comply with the CERN safety standard of requiring that personnel and material, e.g. the carbon steel equipment, be protected from the direct jet of cold helium.

Several Other Consolidations

Additional consolidations were requested in order to operate properly the low-β systems. For instance, 1) the axial movement of the triplet magnets is blocked by bumpers anchored to the tunnel floor. These bumpers were upgraded according to the updated MCI. 2) Helium-guards were installed on the sub-atmospheric circuits to prevent air influx.

3) The integrity of the Plug-In Modules (PIM) was verified after each warm up of the IT. A limit of 150 K temperature differential between the cold bore and the beam screen was requested, especially for the low luminosity points where a cold D1 is used. 4) Mechanical filters were installed on room temperature control valve inlets to prevent contamination to alter the current lead regulation process.

CONCLUSION

The commissioning and first operation of low-β triplets and their electrical feed-boxes at the LHC was performed successfully in 2008. Following the first LHC sector cool-downs, several non-conformities were identified and the requested consolidations have been completed. The operation of the upgraded system has been validated during the first operation. Lessons learned from the first cool-downs permitted us to better understand the behavior of the low-β triplet magnets and their electrical feed-boxes. The optimization of their operation process will be completed when they will be at nominal conditions.

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